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FINAL REPORT
AFT-END IGNITION
LARGE SOLID-ROCKET PROGRAM
PHASE II

Contract No. AF 04(611)-8012

Program No. 623A

Copy No. 23

AEROJET GENERAL TIRE GENERAL

AEROJET-GENERAL CORPORATION

SOLID ROCKET PLANT • SACRAMENTO, CALIFORNIA

A SUBSIDIARY OF THE GENERAL TIRE & RUBBER COMPANY

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Prepared for

AIR FORCE FLIGHT TEST CENTER

EDWARDS AIR FORCE BASE, CALIFORNIA

AEROJET GENERAL TIRE GENERAL

SOLID ROCKET PLANT SACRAMENTO, CALIFORNIA

A SUBSIDIARY OF THE GENERAL TIRE & RUBBER COMPANY

PREFACE

Acknowledgment is made to the following persons for their contributions to the preparation of this report: D. Nachbar, project engineer; D. Wilson and H. Taback, technical support; C. T. Lavinski and A. Plumley, contributions on gas dynamics; and D. Hollister, technical editing.

ABSTRACT

As part of the Phase II Large Solid-Rocket Program (Air Force Contract No. AF 04(611)-8012), a development program was conducted to provide an aft-mounted ignition system is being designed for a 100-in.-dia solid rocket motor. ~~(100 FW-4)~~[redacted] ~~investigate~~ the gas dynamics associated with aft-end ignition are also being studied. [redacted] igniter gas penetration, gas dynamics, and ballistic performance of the aft-end igniter were demonstrated in a series of open-air and free-volume-chamber test firings. Ignition capability of the aft-mounted igniter was demonstrated in two ignition-test motor firings.

The development program showed that ignition of large solid-rocket motors by aft-mounted pyrotechnic igniters is feasible, and has advantages over the more conventional fore-end ignition. Aft-end ignition provides greater motor reliability because retention and sealing problems of a forward-end high-pressure ignition system are eliminated. In addition, the aft-end igniter design is not limited by size and weight restrictions. As a result of the development program, an aft-end igniter was qualified for motor 100 FW-4.

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I. INTRODUCTION

To demonstrate the feasibility of aft ignition in large solid-rocket motors, the aft-end ignition development program described in this report was conducted as part of the Phase II Large Solid Rocket Program, Contract No. AF 04(611)-8012. The basic concept of aft-end ignition for large motors appeared to be advantageous for several reasons. First, the size and weight of large motor igniters make handling equipment and installation access for forward-end igniters more difficult. Second, the large booster igniters produce high thrust levels against the forward motor chamber boss, adding to the complexity of sealing and retaining hardware design. Finally, installation and checkout procedures are greatly simplified in an aft-mounted igniter, since it is located on the launching facility.

II. PROGRAM SUMMARY

Two igniter designs were used in aft-end ignition development program, a forward-end Model 51 (Figure 1) and an aft-end Model 52 (Figure 2). The hardware integrity and ballistic performance for both igniter designs were demonstrated in three open-air test firings. The Model 51 igniter was qualified as a 100 FW-4 forward-end igniter in a free-volume-chamber test. The Model 51 and Model 52 igniters were each evaluated as aft-end igniters in a free-volume chamber test. Both igniter designs provided satisfactory aft-ignition performance; however, the Model 52 igniter was selected for use in the ignition-test motors because of its longer duration of chamber pressurization. The effect of an igniter nozzle expansion cone was evaluated in a final free-volume firing. ~~The first~~ results demonstrated that a nozzle expansion cone increases gas penetration.

II, Program Summary (cont.)

The Model 52 igniter was qualified in two ignition-test-motor firings. The ignition-test motors, processed by an economical technique, simulated the initial geometry of motor 100 FW-4, except for segment joints. An igniter aft-mounted fixture, which permits complete withdrawal of the ignition system after igniter burnout, was also qualified in the second ignition test-motor firing.

The aft-ignition development program achieved the principal program objective, which was to provide a qualified aft-end igniter for motor 100 FW-4. Data concerning the gas-dynamic phenomena of aft-end ignition were also obtained. The following conclusions were drawn from the program:

(a) Motor 100 FW-4 would ignite satisfactorily and would have a 0.200- to 0.250-sec ignition interval (fireswitch to 75% chamber pressure).

(b) The Model 51 igniter would give satisfactory forward-end ignition.

(c) Both the Model 51 and 52 igniters would give satisfactory aft ignition, but the Model 52 igniter has a longer duration of chamber pressurization and larger charge weight, making it more desirable.

(d) An Alclojet igniter produces a weak shock wave in a large grain perforation, where the cross-sectional flow area allows complete expansion of the igniter gas.

(e) The igniter-gas sonic velocity at numerous points along the chamber bore during the shock-wave reflection from the forward head can be used as a measure of gas penetration.

II, Program Summary (cont.)

(f) The igniter gas penetration is primarily dependent on the internal igniter pressure, not on charge weight or burning duration.

(g) The use of an igniter nozzle exit cone allows the shock to form deeper into the bore, thus improving gas penetration.

(h) The technique used to process the ignition-test motor was fast and economical, and can be applied to test motors of all sizes with various grain configurations.

(i) The technique for sizing and predicting Alclojet igniter ballistic performance is fairly well defined.

(j) Substitution of a fast-burning propellant for the Alclo formulation as the main igniter pyrotechnic charge will improve reproducibility and give longer burning durations at a more constant pressure.

(k) Igniter designs for exceptionally large motors can be confidently qualified in free-volume-chamber tests.

III. PROGRAM SCOPE

A. OBJECTIVE

The primary objective of the development program was to provide an aft-mounted ignition system capable of reliably igniting motor 100 FW-4. Other information desired from the program was:

(1) Gas-flow conditions during aft ignition
(2) Igniter gas penetration up the motor bore
(3) Igniter charge-weight requirements for aft ignition
(4) Effects of igniter duration and mass-flow rate on aft-ignition performance

III, Program Scope (cont.)

B. APPROACH

The criteria used for selection of the 100 FW-4 aft-end igniter were that the igniter should be capable of producing a centralized flame pattern, an extended duration, and a reasonable mass flow. Several igniter concepts capable of meeting these criteria were considered, including Alclo grain, Alclojet, and propellant igniters. The Alclojet igniter was selected principally because of its successful performance in the Phase I portion of the Large Solid Rocket Program. Besides fulfilling the criteria discussed, the basic Alclojet igniter components (both inert hardware and pyrotechnics) required little or no development. The other types of igniters would require development of suitable hardware and propellant.

Two Alclojet igniter designs were used in the aft-ignition development program. Since the 100 FW-4 motor would be tested regardless of the aft-ignition-program results, a forward-end igniter, Model 51, was designed and qualified for the motor. This forward-end Model 51 igniter then served as a control for the aft-end free-volume-chamber tests, and was also used as the first-aft end igniter. The second igniter, Model 52, was designed specifically for aft-end application, with increased duration and charge weight. Both igniter designs were evaluated in a series of open-air and free-volume-chamber firings. The most satisfactory design, Model 52, was evaluated in a final free-volume test and in the ignition-test motors.

The foremost problems in obtaining satisfactory aft-end ignition are firing duration of the igniter and penetration of the gases into the motor-chamber free volume. The Mod 52 Alclojet igniter was designed for extended duration and gas penetration was increased by accelerating and directing the igniter gas stream with a nozzle exit cone. Although satisfactory ignition can be obtained even if a portion of the grain is ignited, a more reproducible and reliable motor ignition performance is obtained if nearly all the propellant grain is ignited. If the igniter gas flow is sustained with sufficient pressure, most

III, B, Approach (cont.)

of the propellant surface will be ignited. The gas-flow conditions existing during aft-end ignition may prevent ignition of a sufficient portion of the propellant because the air in the bore, which is cooler, becomes trapped by the igniter gas front. If this trapped air is released too soon, rapid cooling of the propellant surface may result in poor ignition performance. This does not occur during forward-end ignition since the igniter gas front passes over the propellant surface, displacing the motor air column out the motor nozzle.

Propellant cooling during aft-end ignition was indicated in a preliminary test in the 100 FW-2 free-volume chamber. A 7100-gm Model 47B 100 FW-2 igniter was mounted in the aft end of the free-volume chamber. Propellant patches were placed at various stations along the chamber bore. Post-firing examination showed that the propellant patches in the forward end failed to ignite. Also, from the condition of the patches in the aft section of the chamber, it appeared that the patches either ignited and then were extinguished by the cool air or the propellant was eroded away by the igniter gas without being ignited.

C. TEST PLAN

As discussed in Section III, B, two basic Alclojet igniter designs were evaluated in the program: (1) the Model 51, designed for both forward and aft-end application, and (2) the Model 52, designed specifically for aft-end use. The basic aft-end ignition test program is shown in Table 1. The test program was devised to give the desired igniter data with a minimum number of tests.

Both igniter designs were qualified by open-air ballistic firings. The purpose of the open-air firings was to check hardware integrity and ballistic performance prior to committing the design to further free-volume chamber tests.

III, C, Test Plan (cont.)

Following the open-air firings, both igniters (with exit cones) were aft-mounted in a free-volume chamber simulating the initial geometry of motor 100 FW-4 and fired. The free-volume chamber data provided information concerning motor pressurization, gas penetration, gas velocity, ignition capability, and ballistic performance. The Model 51 design was also tested as a forward-end igniter in the free-volume chamber to qualify its capability as a backup.

The final free-volume-chamber test was conducted with the igniter design that gave the most satisfactory performance in the previous tests. The nozzle expansion cone was deleted, so that a gas dynamic evaluation could be made on the effect of an exit cone. (The original proposed program called for two free-volume-chamber tests without the exit cone. However, in anticipation of the necessity for an exit cone, the original test program was revised to conduct two of the three aft-end free-volume tests with an exit cone installed.)

The ignition-test-motor firings demonstrated the igniter performance in a large solid-rocket motor and qualified the igniter design for use in motor 100 FW-4.

IV. DESIGN

A. IGNITER

1. Model 51

a. Description

The Model 51 igniter design is shown in Figure 1. The ignition train was as follows:

IV, A, Igniter (cont.)

Squib	one Holex 2807
Initiator	2.0 gm powder 45% barium chromate 5% boron 50% Alclo
Booster initiator	25 gm AS1094-6 Alclo pellets
Booster	70 gm AS1094-16 Alclo pellets
Main charge	5000 gm 1/360565-1 Alclo pellets

The main igniter chamber consisted of an outer shell and perforated inner tube fabricated from AISI 4130 steel tubing, heat-treated to 170 to 190 ksi ultimate tensile strength. The pellets were installed between the inner and outer portions of the main chamber assembly, with plastic spacers between the pellet rows to reduce attrition. The booster-chamber design was similar, only smaller. The end of the main chamber was threaded to permit attachment of the exit cone. Both the main chamber and booster-chamber assemblies were successfully hydrostatically tested to 10,000 psi.

The adapter plate was fabricated from AISI 4340 steel bar, heat-treated to 170 to 190 ksi ultimate tensile strength. The adapter was designed to be installed in the 100 FW-4 forward-head igniter boss, and provisions were made for measuring internal igniter pressure and forward-end chamber pressure. A mechanical safe-arm system was incorporated in the igniter adapter for safe igniter handling and installation. The device allows the igniter to remain installed in the motor during motor chamber-pressure checks. For firing, the squib gases actuate a piston, which opens the path to the initiator. With the system in the safe condition, the piston is restrained by a safety plug. Should the squib inadvertently fire, the piston O ring prevents the squib gases

IV, A, Igniter (cont.)

from reaching the initiator. The system is armed by removing the safety plug and sealing the cavity with an arming plug.

The expansion-cone half-angle was arbitrarily set at 15 degrees, with a 9:1 expansion ratio (ratio of cone exit area to throat area). The exit cone was fabricated from 4130 steel.

b. Main-Charge Weight

As discussed in Section III, B, the Model 51 was designed primarily as a forward-end igniter. The igniter main-charge weight required to ignite a particular solid-rocket motor is dependent on many parameters, e.g., ignitability of motor peopellant, free volume in the motor, surface area of propellant, and motor-grain length. The charge weight for the 100 FW-4 Model 51 igniter was based on a free-volume correlation, energy delivery to propellant surface, and motor length. On the basis of the free-volume correlating equation

$$W_I = kV_o$$

Where W_I = main-charge weight

V_o = motor free volume

k = constant

an adequate igniter charge weight for the forward-end igniter was found to be 5000 gm. The free-volume correlating equation is shown graphically in Figure 3, with igniter charge weights versus motor free volumes for several Aerojet-General programs.

The 5000-gm main charge was then checked to determine if enough heat was available to the propellant surface at a sufficient rate to ensure ignition. The curve showing total igniter-energy versus igniter-energy delivery rate (Figure 4) was derived from ignition-energy data from many programs.

IV, A, Igniter (cont.)

The total igniter energy was based on 2.18 kcal/gm heat output for Alclo pellets. The total energy rate was based on 0.050 sec effective burning time for the Model 51 igniter. The calculations for total igniter energy and energy delivery rate are also shown in Figure 4. The computed Model 51 igniter energy versus energy rate was well above the upper marginal limit, thus giving further indication that the selected charge weight of 5000 gm was satisfactory.

The final consideration in charge-weight selection was the overall propellant grain length of the motor. A summary of large solid-rocket motor dimensions and igniter charge weights, including percentage increase or decrease for each dimension, is presented in Table 2. The free volume and surface area for motors 100 FW-1 and -2 were essentially the same, and it appeared that an increase in igniter charge weight was unnecessary. However, the poor results obtained in free-volume-chamber tests on the 100 FW-2 igniter necessitated a charge-weight increase for motor 100 FW-2. The parameter dictating the need for an increased charge weight appeared to be the additional grain length exposed to the igniter flame front. The same correlation was evident in the charge weights required for motor 100 FW-3. From free-volume and surface area, it appeared that a 45% charge-weight increase would be sufficient for 100 FW-3. However, because of the extended grain length, the additional charge was necessary. Ignition performance in both motors 100 FW-2 and -3 indicated that the charge-weight selections were sound. Comparing the dimensions of motor 100 FW-2 and -4, a 29% decrease in charge weight was reasonable. Since there was also 20% decrease in grain length, the main-charge weight for motor 100 FW-4 could be safely reduced another 10%. Thus, on the basis of grain-length considerations, the selected 5000-gm main-charge weight was well above the minimum charge weight.

c. Ballistic Design

The ballistic design of the Model 51 Alclojet igniter is presented in Table 3. A 360565-1 stoichiometric Alclo pellet, shown in Figure 5,

IV, A, Igniter (cont.)

was selected for the Model 51 igniter. The expected maximum internal pressure in the Model 51 igniter was 6000 psi, with an average overall operating pressure of 2000 psi. Thus, the expected igniter burning duration was 0.05 sec (Table 3.)

2. Model 52

a. Description

The Model 52 igniter design is shown in Figure 2. The ignition train was as follows:

Squib	one Holex 2807
Initiator	2.0 gm powder 45% barium chromate 5% boron 50% Alclo
Booster Initiator	25 gm AS1094-6 Alclo pellets
Booster	114 gm, AS1094-16 Alclo pellets
Caim charge	8500 gm 1/362842-3 Alclo pellets

The main igniter chamber consisted of an outer shell and perforated inner tube. The outer shell was fabricated in three sections from 4130 forged steel, welded and heat-treated to 160 to 180 ksi ultimate tensile strength. The perforated inner tube was fabricated from 4130 seamless steel tubing. The assembly was internally hydrostatically tested to 8000 psi. Because of the anticipated longer igniter burning duration, the inner surface of the outer shell was insulated with 0.25-in.-thick Thermomat 461-193. The Alclo pellets were installed in the annulus between the outer shell and the inner tube.

IV, A, Igniter (cont.)

The igniter closure was fabricated from 4130 forged steel, heat-treated to 160 to 180 ksi ultimate tensile strength. The closure face was insulated with Gen-Gard V-44 rubber, and a reinforced phenolic-resin throat insert was bonded to the closure exit area. The closure assembly was bolted to the chamber assembly.

The booster chamber and booster adapter were fabricated from 4130 forged steel and seamless steel tubing, heat-treated to 170 to 190 ksi ultimate tensile strength. The booster assembly, including adapter, chamber, and squib, was installed in the head end of the main chamber assembly through a thread joint and an O-ring seal.

The exit-cone half-angle was 15 degrees, with a 6:1 expansion ratio. The closure was threaded to permit attachment of the exit cone. Again, the half-angle and expansion-ratio selection was arbitrary.

b. Main-Charge Weight

The main-charge weight selected for the Model 52 igniter was 8500 gm. There were no available criteria on which to base a charge-weight selection for an aft-end igniter. As discussed in Section IV, B, to ensure ignition of most of the propellant grain, it was considered necessary to extend the burning duration of the aft-end igniter and maintain a reasonable mass-flow rate. The curve showing total energy versus energy delivery rate (Figure 4) indicates that if the Model 51 igniter burning duration is increased without a corresponding increase in the pyrotechnic charge weight, unsatisfactory ignition could result. Therefore, from an energy-delivery-rate standpoint, an increase in burning duration must be accompanied by an increase in igniter charge weight. In the case of the Model 52 igniter, a 6500-gm main charge at a 0.100-sec burning duration would provide an adequate energy output to the motor propellant. However, as there were several unknowns regarding aft igntion such as optimum mass-flow rate and gas penetration, the Model 52 final igniter charge-weight selection was substantially greater to ensure a generous

IV, A, Igniter (cont.)

safety factor. The large Model 52 igniter charge weight would be particularily advantageous in the event the Model 51 igniter failed to give satisfactory aft-ignition performance. The combination of the 362842-3 Alclo-pellet size and weight led to the final 8500-gm selection, in which three rows of six pellets were conveniently oriented.

c. Ballistic Design

The ballistic design of the Model 52 Alclojet igniter is presented in Table 4. A 362842-3 Alclo pellet, shown in Figure 5, was selected for the aft igniter. A newly developed Alclo formulation was used for the Model 52 igniter pellet instead of the usual stoichiometric formulation. The new formulation, called Type 0-041, consists of 25% Aluminum 800; 5% Aluminum 101; 59.4% $KClO_4$; 4.6% iron; and 6.0% lead. This improved formulation has a burning-rate exponent of 0.484 at operating pressures over 1000 psi, compared with exponents of 1.1 for stoichiometric Alclo and 0.57 for Alclo-iron in the same pressure range. The Type 0-041 Alclo has shown much greater reproducibility in test firings. The addition of atomized aluminum (Aluminum 101) significantly improved the physical strength of compacted pellets.

A K ratio (ratio of total burning surface area to nozzle throat area) of 45 was selected for the Model 52 igniter, which was considerably lower than the K ratio of 100 selected for the Model 51 igniter. A lower K ratio was possible because of the larger pellet size and the longer burning duration. At the 45 K ratio, the predicted maximum pressure was 4000 psi.

B. FREE-VOLUME-TEST CHAMBER

The 100 FW-4 free-volume-test chamber is shown in Figure 6. The 40-in.-dia by 406-in.-long test chamber was composed of two sections (100.5 in. long and 305 in. long) of the 100 FW-1 free-volume chamber bolted together. A nozzle exit-cone section was welded to the aft-end plate. A 100 FW-4 igniter boss was fabricated and installed on the test-chamber forward head.

IV, B, Free-Volume-Test Chamber (cont.)

During each of the free-volume firings, the chamber bore was instrumented at various stations (Figure 6). The instrumentation at each station included a pressure transducer, a gold-button calorimeter, and a propellant patch. The gold-button calorimeters had either an-iron constantan or a chromel-alumel thermocouple. The propellant patches (Figure 7) consisted of metal containers cast with ANP-3025 JY (motor 100 FW-4) propellant which were threaded into a small boss in the chamber wall.

C. IGNITION-TEST MOTOR

The 40-in.-dia ignition-test motor (Figure 8) simulated the geometry of motor 100 FW-4 propellant grain, except for the segment joints. The motor consisted of a forward head, six cylindrical center sections, and an aft closure. The sections were bolted through flange joints to make the final motor assembly. O rings were installed in the flange grooves to seal the joints against leakage.

The forward-head and aft-closure sections were fabricated from 4130 steel, with plate stock used for the flanges. The cylindrical portions of both the forward head and aft closure were made from plate stock, rolled into a cylinder and welded along the axial joint. The head portions for both ends were deep-drawn. The nozzle portion of the aft closure was fabricated from a rolled-ring forging. All of the portions for both the forward head and aft closure were welded, X-ray inspected, stress-relieved at 1100 to 1200°F for 2 hr, air-cooled, and final-machined to drawing specifications.

The rolled-and-welded cylindrical sections were fabricated from Cor-Ten low-alloy, low-carbon-content steel. The flange material was 4130 steel plate.

The final motor assembly was then hydrostatically tested to 400 $\pm$ 5 psig for 10 sec in the horizontal position.

IV, C, Ignition-Test Motor (cont.)

The 40-in.-dia ignition-test motor design called for a 1/2-in.-thick web of propellant, which would give approximately 2 sec of progressive burning. A preliminary study was conducted to determine if the ANP-3025 JY propellant could be cured in 21-in.-wide by 60-in.-long trays and then bonded to the chamber-wall liner material. The preliminary tests were very successful and indicated this approach to ignition motor processing was satisfactory.

The inner surface of 1/2-in.-deep wooden trays was lined with polyethylene sheeting. Since the propellant in motor 100 FW-4 is cured against a polyethylene-bagged core, it was necessary to follow the same procedure for the ignition-test motor to ensure similar propellant-surface characteristics. Racks were provided to stack the wooden trays during propellant cure.

The ANP-3025 JY propellant was mixed, cast into the trays, and cured at 110°F for 96 hr. The trays were vibrated during casting operations and the propellant was leveled after casting. Just prior to installation of the propellant, the motor chamber walls were coated with SD-746M liner. The propellant strips were manually removed from the trays and laid up in the chamber with the surface adjacent to the polyethylene sheeting exposed. All propellant joints were neatly and tightly butted together. The liner system was then cured at 110°F for 72 hr.

The aft-closure section was insulated with 1/2-in.-thick trowelable NRL-1126 (Nobell Research Laboratory) insulation. The nozzle-throat and exit-cone surfaces were sprayed with 200- to 300-mesh zirconium oxide.

Provision was made in the chamber wall, liner, and propellant surface to permit pressure measurements at various stations along the chamber bore and at the forward end.

At the conclusion of the first ignition-test motor firing, the sections were chemically cleaned and then reprocessed.

IV, Design (cont.)

D. IGNITER MOUNTING FIXTURE

The criteria used for design of a mounting fixture were as follows:

1. The fixture had to retain the igniter in position for at least 0.150 sec, as the igniter duration would not exceed this value.

2. The fixture had to be pad-mounted and not attached to the exit cone or any part of the motor.

3. The fixture had to be capable of removing the igniter from the exit cone by a remote command so that the igniter would not interfere with motor and thrust-vector-control performance.

Three mounting fixtures were used during the development program. The fixture used for all the free-volume-chamber tests is shown in Figures 2 and 9. The igniter was mounted on a swing arm, which pivoted in a frame bolted to the test bay deck. The swing arm was secured to the fixture frame by explosive bolts. Approximately 0.130 sec after fire switch, the bolts were actuated and the igniter swung clear of the chamber exit cone. The fixture performed satisfactorily during all the free-volume tests; however, because of the size and weight of the swing arm and frame a great deal of fixture setup time was required. Also, the fixture was not adaptable to large exit cones such as 100 FW-4 and would cause interference problems when jet-tab thrust-vector control is used.

The fixture used to mount the igniter in 40 ITM-1 is shown in Figure 10. This fixture was for interim use only and did not meet the specified criteria.

IV, D, Igniter Mounting Fixture (cont.)

The fixture used to mount the igniter in 40 ITM-2 is shown in Figure 11. As shown in the figure, the Model 52 igniter was bolted inside a pipe fitted with four rollers. Two steel H beams were located parallel to the motor center line and supported on the test-bay deck by a steel pipe stand. The igniter was positioned in the motor exit cone with the H beams as roller tracks, and secured by a holding bar equipped with explosive bolts. At approximately 0.130 sec after fire switch, the explosive bolts were actuated and the igniter was ejected from the exit cone by the impingement of the motor gas stream against the igniter exit cone.

V. TEST RESULTS

A. OPEN-AIR TESTS

As previously discussed, the purpose of the open-air tests was to verify igniter ballistic performance and hardware integrity. A typical open-air test setup is shown in Figure 12. Three open-air tests were conducted, two tests on the Model 51 igniter and one test on the Model 52. The instrumentation on each open-air test included internal igniter operating pressure and igniter thrust. The results of the three open-air firings are tabulated below:

Igniter model No.	51	51	52
Test No.	1	1 (repeated)	2
Maximum internal igniter chamber pressure, psig	5750	5520	4350*
Maximum igniter thrust, lb	48,500	42,600	53,483
Time from fire switch to maximum internal igniter pressure, sec	0.024	0.025	0.034
Time from fire switch to initial internal igniter pressure rise, sec	0.016	0.015	0.016

*Pressure tap was plugged, and pressure was calculated from the thrust value.

V, A, Open-Air Tests (cont.)

Duration,** sec	N/A	0.055	0.105

The igniter performance cures for the open-air tests are shown in Figure 13 through 15. In the first Model 51 open-air test, the igniter chamber separated from the adapter approximately 0.025 sec after fire switch. The performance curve (Figure 13) showed that the igniter had attained maximum expected pressure before failure occurred. Postfiring inspection indicated a one-to-two thread engagement between the chamber and adapter. Subsequent inspection of other Model 51 hardware revealed an interference between the adapter booster attachment boss and the retainer used to hold the main-charge pellets in place. This interference prevented minimum required thread engagement between the chamber and adapter, and was corrected on all remaining Model 51 hardware. The Model 51 open-air test was repeated to ensure hardware integrity and to verify the ballistic data obtained in the first test.

The ballistic results from the open-air tests were very satisfactory and agreed fairly well with the design values shown in Tables 3 and 4, as summarized below:

	Design	Test
Model 51		
Maximum internal igniter pressure, psi	6000	5750, 5520
Duration, sec	0.053	0.049
Model 52		
Maximum internal igniter pressure, psi	4000	4350
Duration, sec	0.103	0.105

**Duration is defined as the time from start of main igniter-charge pressure rise to the time when the tailoff pressure reaches about 10% of maximum pressure.

V, Test Results (cont.)

B. FREE-VOLUME-CHAMBER TESTS

1. Forward End

The first free-volume-chamber test was conducted to evaluate the Model 51 performance as a backup forward-end ignition system for motor 100 FW-4. The igniter performance is summarized below:

Igniter model No.	51
Test No.	3
Maximum internal igniter chamber pressure, psig	5814
Time from fire switch to maximum internal igniter pressure, sec	0.030
Time from fire switch to initial internal igniter pressure rise, sec	0.015
Duration, sec	0.056

The igniter performance curve is shown in Figure 16. The data obtained from the free-volume-chamber instrumentation is shown in Table 5, column 1. The test results were very satisfactory; all propellant patches ignited and the igniter ballistic performance was reproducible with respect to design prediction and previous open-air tests. On the basis of this free-volume test, the Model 51 igniter will give satisfactory forward-end ignition performance if required.

2. Aft End

Three aft-end free-volume chamber tests were conducted in the development program. As shown in the Test Plan (Table 1) an aft-end free-volume-chamber test was conducted for both the Model 51 and 52 igniters

V, B, Free-Volume-Chamber Tests (cont.)

with the exit cone included. On the basis of the results of these tests, a final free-volume-chamber test was conducted on the igniter that gave the more desirable aft-ignition performance. The exit cone was deleted from the final test. The igniter performance results of the first two free-volume-chamber tests are as follows:

Igniter Model	51	52
Test No.	4	5
Maximum internal igniter chamber pressure, psig	5696	3350
Time from fire switch to maximum internal igniter pressure, sec	0.022	0.036
Time from fire switch to initial internal igniter pressure rise, sec	0.013	0.020
Duration, sec	0.055	0.102

The igniter performance curves are shown in Figures 17 and 18. The data obtained from the free-volume-chamber instrumentation is shown in Table 5, columns 2 and 3. The aft-end ignition performance of both igniters was satisfactory. Again, the peak pressure and duration of the Model 51 igniter was reproducible and agreed with predicted design values and previous firing results. The duration of the Model 52 was in line with predicted design and the previous test durations; however, the peak pressure was somewhat lower than predicted.

In both tests, the two forward propellant patches failed to ignite and the calorimeters in the same location indicated a negligible temperature rise. On the basis of the forward-end pressure data (Figure 19) and the failure of the propellant patches to ignite, it appeared that the air column within the free-volume chamber was being trapped and compressed into the forward end, with apparently little circulation. The igniter gas front compressed the air

V, B, Free-Volume-Chamber Tests (cont.)

column much like a piston, and continued the compression until the air pressure overcame the gas front pressure. The final chamber air column volume, when compressed adiabatically from 14.7 to 100 psi, would be approximately one third of the initial air volume. On the basis of calorimeter and propellant-patch data, it appeared that the aft two thirds of the free-volume chamber was exposed to the igniter gases, whereas the forward one third was not. Also the forward chamber pressure level was essentially the same as pressures measured at other stations, yet there was little or no diffusion of igniter gases into the volume occupied by the compressed air.

The pressure-vs-time curves at each station for both free-volume tests are presented in Figure 19. The Model 52 igniter maintained chamber pressure from 0.040 to 0.070 sec longer than the Model 51, thus exposing the propellant surface to the igniter gases for a longer period of time. The longer exposure should permit stable propellant burning to be established before the trapped cool air is released. If the trapped air is released before stable propellant burning is established, undesirable ignition characteristics may result. Therefore, on the basis of longer chamber pressurization, the Model 52 igniter was selected for the final aft-end free-volume-chamber test.

The final free-volume-chamber test was conducted to evaluate the performance of the Model 52 igniter without a nozzle exit cone. The igniter performance results of the final test are as follows:

Igniter Model	52
Test No.	6
Maximum internal igniter chamber pressure, psig	4884
Time from fire switch to maximum internal igniter pressure, sec	0.028

V, B, Free-Volume-Chamber Tests (cont.)

Time from fire switch to initial internal igniter pressure rise, sec	0.018
Duration, sec	0.080

The igniter performance curve is shown in Figure 20. The data obtained from the free-volume-chamber instrumentation is shown in Table 5, column 4. The pressure-vs-time curve for each chamber station is presented in Figure 21.

The test results indicated that the propagation of the pressure front was slower when the exit cone was omitted, which was expected. The failure of the Station 3 propellant patch to ignite demonstrated the poorer penetration of the igniter gases. The flame front was more turbulent, whereas the exit cone provided a uniform flame propagation up the bore of the chamber at a greater velocity. There is little doubt that satisfactory ignition could be accomplished with a Model 52 igniter without an exit cone; however, to ensure maximum gas penetration and propellant surface exposure, an expansion cone will be used in all future aft-end tests.

C. IGNITION-TEST MOTORS

1. 40 ITM-1 Ignition

Ignition of 40 ITM-1 was accomplished by a Model 52 igniter with a nozzle expansion cone. The igniter was aft-mounted into the motor exit cone by a fixture bolted directly to the test bay, as shown in Figure 10. No attempt was made to remove the igniter from the motor exit cone during the test. The exit plane of the igniter exit cone was located 5 in. from the plane of the motor throat, thus giving a minimum free flow area around the igniter of 1.1 times the nozzle throat area.

V, C, Ignition-Test Motors (cont.)

Ignition of 40 ITM-1 was satisfactory; the ignition delay was 0.320 sec at a 475-psi/sec rate of motor pressure rise. The igniter performance curve is shown in Figure 22 and the motor performance curve is shown in Figure 23. A postfiring photograph of motor 40 ITM-1 is shown in Figure 24. The postfiring condition of the motor was excellent, with no visible hot spots or evidence of section-joint leakage. The igniter and mounting fixture, found about 900 ft from the test bay, were badly damaged (Figure 25).

Approximately 0.026 sec after fire switch, the 45-degree fitting connecting the pressure transducer to the igniter pressure tap burned out at the angle junction. In all previous tests, a straight-union fitting was used. Interference between the igniter and the mounting fixture necessitated the use of an angled fitting. If this same malfunction had occurred in a forward-end igniter, the motor would probably have failed because of burnout of the adapter. However, since the igniter was not an integral part of the motor, the pressure-fitting burnout did not affect motor performance.

2. 40 ITM-2 Ignition

The 40 ITM-1 sections were cleaned and reprocessed with propellant strips for 40 ITM-2.

The igniter design for ignition of motor 40 ITM-2 was unchanged from the 40 ITM-1 test. The igniter was retained in the motor exit cone by the mounting fixture described in Section IV, D, of this report and shown in Figure 11. The free flow area around the igniter in motor 40 ITM-1 prevailed in this firing.

Although an instrumentation malfunction at 0.215 sec resulted in loss of all pressure data after that time, a sufficient amount of valid data were obtained to evaluate the ignition performance. The ignition results for 40 ITM-2 are shown below. Ignition results from 40 ITM-1 are included for discussion purposes.

V C, Ignition-Test Motors (cont.)

	40 ITM-1	40 ITM-2
Ignition interval, sec	0.320	0.140
Rate of pressure rise, psi/sec	475	1180

The 40 ITM-2 ignition was satisfactory and considerably faster than 40 ITM-1. There was no apparent explanation for the 0.180-sec variation in the ignition performance other than a considerable difference in individual igniter ballistic performance. Observation of the 40 ITM-2 firing and postfiring inspection of the motor indicated normal ignition and motor performance. A postfiring photograph of the motor is shown in Figure 26. Camera coverage of the ignition sequence is presented in Figure 27. Since all evidence pointed to a normal firing, the pressure data after the instrumentation malfunction should be similar to 40 ITM-1 data.

The motor chamber pressure-vs-time curves for 40 ITM-1 and -2 are presented in Figure 28. The aft-end free-volume-chamber pressure data are also included. Analysis of the pressure-vs-time curves indicated that the ignition performance in both motors was essentially the same. The forward-end transducer failed to respond to the initial pressure shock; however, the instrumentation located 21 in. from the forward head measured similar pressure shocks at relatively the same time in both motors. In both firings, motor ignition occurred about 0.070 sec after fire switch. The 40 ITM-2 chamber pressure at the time of ignition was about 50 psi greater than in 40 ITM-1, resulting in a faster rate of pressure rise. The pressure curves for both motors compare favorably with the pressure curve obtained in the free-volume chamber, with only a negligible difference in the time interval.

The aft-mounting fixture performed as designed. At 0.120 sec after fire switch, the explosive bolts holding the restraining bar were actuated and the igniter assembly was ejected from the motor exit cone. The assembly was found embedded in the ground about 100 yds from the test bay, as shown in Figure 29. The same design will be used to mount the igniter into the 100 FW-4 motor exit cone.

V, Test Results (cont.)

D. IGNITER-GAS DYNAMICS

A study of the igniter-gas dynamic phenomena in the three aft-end free-volume-chamber tests was made to develop a generalized theory for the application of aft ignition to motors of other sizes. Some qualitative trends were established within the boundary of igniter variation. Principally, the investigation was conducted to determine the depth of igniter-gas penetration and to evaluate the effects on this penetration of such variables as igniter exit cone, internal igniter chamber pressure, and igniter charge weight.

Qualitatively, the initial analysis consists of the following model. When gas is expelled from the igniter, a shock is formed, and is propagated up the bore at a faster velocity than the hot gas. Assuming that there is no mixing of the hot and cold gas in the bore, the conditions in the bore at this time are pictured in Figure 30A. The shock continues up the bore and is reflected off the forward head. If the shock is weak and the igniter-gas generation is continued during this period, the pressure behind the shock is relatively constant and no rarefaction wave is initiated. After the shock is reflected off the forward head, it meets the interface and passes through the hot gas, as shown in Figure 30B. This will cause a reduction in the hot-gas penetration velocity, depending on the shock strength. With extended controlled igniter gas generation and corresponding weak shocks, rarefaction waves are possible but unlikely.

The test data concurred generally with this model; however, to obtain a more quantitative criterion for aft-end ignition, a more extensive program would be required in which:

1. Such parameters as peak ignition pressure, shape of the igniter pressure-vs-time curve, and duration were varied independently.

V, D, Igniter-Gas Dynamics (cont.)

2. The parameter variation would be extensive enough to significantly affect the gas dynamics

3. Additional instrumentation would be used, such as more propellant patch and strain gages on the case to record shock wave propagation

4. The free-volume chamber would be shock-mounted to reduce the noise in the pressure transducers.

Such a program would require many more tests than are possible in this program and should probably be conducted with igniters containing a main charge of approximately 100 gm instead of the 5000- and 8500-gm charge used on these igniters.

The configuration of the free-volume test chamber was described in Section IV, B, and the instrumentation station locations were shown in Table 5. As discussed previously and shown in Table 5, four out of six propellant patches were ignited in tests No. 4 and 5, and only three of the patches were ignited in test No. 6 when the nozzle exit cone was omitted. The shape of the igniter pressure-vs-time curves for test No. 5 (Figure 18) and test No. 6 (Figure 20) were significantly different, so that the effect of the exit cone or the pressure curve cannot be quantitatively singled out. The propellant-patch ignition gave some indication of igniter gas penetration; yet, when four propellant patches were ignited, it could not be established if the igniter gas had penetrated to the length covering just those four patches or if the gas had almost reached the fifth patch. The distance between the stations No. 3 and 2 patches was 76.9 in. Calorimeters were also located at each station but did not respond until sometime after the igniter had ceased burning. Thus, the calorimeter was not useful in determining the rate of hot-gas propagation up the bore. The failure of the forward calorimeters to respond indicated that the hot gas had not penetrated to that region.

V, D, Igniter-Gas Dynamics (cont.)

The pressure traces from each of the three tests were used to determine the incident and reflected shock velocities in the chamber bore. Because of the temperature differential between the hot and cold gas in the chamber bore and a consequent sonic gas velocity variation, the depth of igniter gas penetration could be related to the time required for the reflected shock to traverse the length of the chamber. With high-quality pressure data, the shock velocity from station-to-station and the variation in sonic velocity due to temperature differential along the chamber could be determined. This would provide a direct measure of igniter-gas penetration. From the pressure data obtained from the three aft-end free-volume chamber tests, it was impossible to ascertain the time at which the reflected shock passed some of the stations. Therefore, it was necessary to average the velocity over the entire chamber, providing a means to compare only the relative depth of penetration.

The mean sonic velocity ranged from 1300 to 2100 ft/sec for the three tests. On the basis of this criterion, the Model 51 igniter in test No. 4 provided the deepest penetration. This igniter had an exit cone, achieved the highest peak internal igniter chamber pressure, and formed the strongest shock wave of the three tests. This agreed with the one-dimensional-shock theory, in that the gas velocity behind the shock increases relative to the shock strength so higher gas penetration with the Model 51 igniter would be expected. The Model 52 igniter without the exit cone (test No. 6) appeared to have the next deepest penetration, on the basis of mean sonic velocity, and correspondingly had the next highest peak internal igniter chamber pressure. This igniter did not ignite the station No. 3 propellant patch, whereas the other Model 52 with an exit cone (Test No. 5) penetrated less and still ignited the station No. 3 propellant patch. This anamoly appears to be due to the inaccuracy introduced by the use of a mean sonic velocity rather than a station-to-station calculation.

The pressures at the aft-end station No. 6 decreased before the igniter reached peak internal chamber pressure in tests No. 4 and 5. In both of these tests the nozzle exit cone was used, and the early station No. 6 pressure

V, D, Igniter-Gas Dynamics (cont.)

decrease was attributed to overexpansion of the igniter gas flow. Without an exit cone, it appeared that the shock is formed and subsonic flow begins nearer the aft end. This indicated the hot-gas flow field is supersonic and is at a lower density for a longer period when the exit cone is used. Therefore, the subsonic flow region started deeper in the bore, which enables better gas penetration.

The tests conducted were comparable only from the standpoint of the 100 FW-4 motor configuration. Unfortunately, it was not possible to vary a single parameter with respect to other parameters, and the varying values of individual parameters were not great enough to quantitatively describe their effect on gas dynamics because of the limited number of tests in the program. The basic structure of the test plan was concentrated on the qualification of an aft-end igniter for 100 FW-4, with gas dynamic data obtained as a supplement to the basic objective. In a pure aft-ignition research program, this quantitative data could be obtained at less cost by using smaller igniters and test equipment, where wider variations in parameters is more feasible.

VI. CONCLUSIONS

A. GENERAL

The overall results of the aft-ignition development program were very satisfactory; the primary program objective was fulfilled and the efficacy of the aft-end ignition system was demonstrated by the successful ignition of the test motors. The performance data obtained from the program test plan indicated that the approach taken to aft ignition of large motors was sound. The test program proved to be well-established, as the program objectives were adequately fulfilled through a minimum number of firings.

On the basis of the results of the aft-ignition program, the predicted ignition performance curve for motor 100 FW-4 is shown in Figure 31. The

VI, A, General (cont.)

motor chamber pressure was estimated from the free-volume and ignition-motor tests prior to ignition. Ignition should occur at about 0.070 sec after fireswitch and motor chamber pressure should reach 75% of initial operating thrust (ignition interval) between 0.200 and 0.250 sec, assuming a 750- to 2000- psi/sec.

B. IGNITER DESIGN

1. Model 51

The Model 51 igniter design is satisfactory in every respect, giving reliable and reproducible ballistic performance. The Model 51 igniter ballistic performance is summarized below:

	Maximum Operating Pressure, psig	Duration, sec
Design	6000	0.053
Test No. 1	5720	-----
Test No. 1A	5520	0.055
Test No. 3	5814	0.056
Test No. 4	5696	0.055

These results indicate that the design basis for predicting Alclojet igniter performance is fairly well defined and that the minor variations in ballistic performance are easily attributed to the individual component tolerances. The successful Model 51 free-colume-chamber tests show that the main-charge selection is more than adequate. The method of selecting igniter charge weights based on a combination of motor dimensions has proven very sound, thus enabling the designer to accurately size and predict igniter performance for any application, regardless of size.

The test program not only demonstrated that the Model 51 igniter will provide satisfactory forward-end ignition, but, as the aft-end free-volume test indicates, may also provide adequate performance as an aft-end

VI, B, Igniter Design (cont.)

Igniter. If additional funds has been available, an aft-end Model 51 igniter would have been used to ignite motor 40 ITM-3. This test would have determined if the shorter igniter burning duration was capable of providing adequate aft-ignition performance. If this capability were shown, an igniter design based on forward-end-design criteria could be used equally well in either forward- or aft-end applications.

2. Model 52

The Model 52 igniter performance in free-volume and ignition motor tests was very satisfactory, however, the igniter ballistic reproducibility of the various firings was less than desired. The ballistic results are summarized below:

	Maximum Operating Pressure, psig	Duration, sec
Design	4000	0.103
Test No. 2	4350*	0.105
Test No. 5	3350	0.102
Test No. 6	4884	0.080
40 ITM-1	Pressure-fitting burnout	-----
40 ITM-2	Instrumentation malfunction	-----

*Calculated from Thrust Data

The variation in ballistic performance is too great to be attributed to individual component tolerances. The burning-rate control of the Alclo pyrotechnic material has at times been the cause of lack of reproducibility in Alclo-type igniters. However, the current technique in controlling the specific surface of the aluminum and perchlorate particles, particle size, and particle-size distribution during Alclo-pellet manufacture results in a burning-rate variation of only $\pm$ 5.0% over a wide range of pressure levels. As the basic design for both the Model 51 and 52 igniters is essentially the same, the

VI, B, Igniter Design (cont.)

reproducibility variation in the Model 52 appears to be due to the lower free-flow-area to throat-area ratio of 2:8, compared to a 10:1 area-ratio for the Model 51. The free-flow area in an Alclojet igniter is the total area of the main-chamber inner-tube perforations. As shown in Figures 1 and 5, the Alclo pellets are retained in the main-chamber annulus between the outer shell and inner tube, and the combustion gases flow through the inner-tube perforations and are exhausted out the nozzle. It appears that if the free-flow area is too low, a pressure differential is established across the perforations, producing a higher-than-predicted pressure in the annulus containing the pellets. This pressure differential will vary for each particular igniter, depending on the percent of perforations that are blocked by pellet orientation. In contrast, an Alclojet igniter with a large free-flow area does not exhibit excessive pressure variation and the pressure is not significantly affected by pellet orientation. There is no doubt that the Model 52 igniter as presently designed will give satisfactory aft-ignition performance in motor 100 FW-4; however, in future Alclojet igniter designs, a large free-flow area must be provided to ensure ballistic reproducibility.

C. GAS DYNAMICS

The test program provided data with which to analyze the gas dynamic phenomena in aft ignition. The gas-flow data obtained in the free-volume-chamber tests leads to the following conclusions:

1. An Alclojet igniter produces a weak shock (Mach 1.1 to 1.2) in a large propellant grain perforation where the cross-sectional flow area allows complete expansion of the igniter gas.

2. It is assumed that for a particular motor bore configuration, there is an optimum igniter shock strength to produce optimum gas penetration into the bore. There were insufficient tests in the program scope to confirm this assumption or to determine an optimum shock value for the 100 FW-4 motor configuration.

VI, C, Gas Dynamics (cont.)

3. Determination of the igniter gas sonic velocity at numerous points along the chamber bore during the shock-wave reflection from the forward head can be used as a measure of gas penetration.

4. The igniter duration or charge weight are not good criteria for gas penetration, since both long- (Model 52) and short- (Model 51) duration igniters ignited the same propellant patches and achieved approximately the same penetration depth.

5. The use of a nozzle exit cone allows the shock to form deeper into the bore, thus improving gas penetration. In reviewing the overall test program, all program objectives were demonstrated and sufficient data was obtained to permit an analysis of aft-ignition performance. However, in future aft-ignition testing, particularly in free-volume-chamber tests, the instrumentation coverage should be improved as follows to fully understand the ignition mechanism. Strain gages should be mounted at numerous points along the chamber so the shock propagation can be accurately timed. This in turn would permit a more accurate determination of shock velocity and give a measure of gas penetration. Additional propellant patches in the region of gas penetration would yield better penetration data. Shock mounting of the free-volume-chamber pressure transducers would eliminate a great deal of "ringing" in the transducer, and would give a clearer oscillograph record at each station.

D. IGNITION-TEST-MOTOR TECHNIQUE

The ignition-test-motor processing technique described in Section IV, C, has proven to be exceptionally fast and economical. The reprocessing of the motor after the initial firing including chemical cleaning, required only 2 weeks for 40 ITM-2. In other rocket motor programs, the ignition-test motors were processed by first casting the motor chamber with inert propellant. A thin layer of live propellant was then case over the inert propellant into the

VI, D, Ignition-Test-Motor Technique (cont.)

desired configuration. This technique required additional casting tooling, and required a long lead time because of casting facility priority. Reprocessing time usually required about 2 to 3 months.

The ignition-motor processing technique used in the aft-ignition program can be adapted to motors of any size, and by the use of rubber or plastic inserts, can be adapted to a wide range of grain configurations. Ignition motors for super boosters such as the 260-in.-dia motor are economically feasible with this technique.

E. ADVANTAGE OF AFT-END IGNITION

The expected advantages of aft-end ignition that led to the instigation of the program were aptly demonstrated during the development testing. The possible modes of failure and design problems associated with the installation, retention, and sealing of a high-pressure ignition system in the forward motor head are eliminated, thus increasing the overall motor reliability. In past rocket motor programs, several catastrophic motor failures were due to malfunctions in the sealing or retention of the ignition system. Many of these motor failures would have been averted with an aft-mounted igniter, as the malfunctions were limited to the ignition system and normal ignition could have been achieved. This advantage was clearly demonstrated in motor 40 ITM-1, when the igniter pressure fitting burned out. This additional reliability is of prime importance due to the high cost of large solid-rocket motors.

The aft-mounted igniter also permits a greater latitude in design redundancy and conservatism, since igniter size and weight are no longer design limitations. With these limitations removed, the igniter can be designed with a much higher factor of safety. The redundancy in safe-arm and initiator design now available will provide excellent performance reliability.

VI, Conclusions (cont.)

F. FUTURE APPLICATION

The basic aft igniter design is relatively simple. The development program has shown that ignition of large solid-rocket motors with aft-mounted igniters is accomplished by using fairly well defined techniques. The basic aft igniter design is less complex than other systems, and requires minimum ground-support equipment for installation and checkout.

Reliable ignition of super boosters such as the 260- and 360-in.-dia motors with aft-mounted pyrotechnic igniters is possible with current design techniques. To improve individual igniter reproducibility, increase motor chamber pressurization, and extend duration and mass flow it appears highly desirable to substitute a fast burning propellant as the main igniter pyrotechnic charge for large-motor ignition. The redundancy and hardware integrity that can be incorporated into an aft-end igniter design makes this system advantageous for clustered-motor application, where reliable and reproducible motor ignition is essential.

TABLE 1

AFT-END-IGNITION TEST PROGRAM

Test	Igniter	Type of Test	Objective
1	Igniter Model 51 (standard duration)	Open air	Determine igniter performance and integrity
2	Igniter Model 52 (extended duration)	Open air	Determine igniter performance and integrity
3	Igniter Model 51	Free Volume, fore end	Evaluate fore-end-ignition performance (control for aft-end tests)
4	Igniter Model 51	Free Volume, aft end with nozzle exit cone	Evaluate aft-end-ignition performance
5	Igniter Model 52	Free Volume, aft end with nozzle exit cone	Evaluate aft-end-igniter performance
Decision: Select the better igniter from tests no. 4 and 5. Use this igniter without exit cone for test no. 6.			
6	To be selected	Free Volume, aft end without exit cone	Evaluate aft-end-igniter performance without exit cone
Decision: On the basis of free-volume test results, select the better igniter for aft-end ignition. In addition, determine if the igniter exit cone improved ignition performance.			
7	To be selected	Ignition-Test Motor No. 1	100 FW-4 full-scale ignition evaluation
Decision: On the basis of the ITM firing, determine if ignition is satisfactory if modifications are necessary to provide desired performance.			
8	To be selected	Ignition-Test Motor No. 2	To verify previous ignition performance or to evaluate design modifications
9	To be selected	Ignition-Test Motor No. 3	To verify selected igniter performance if required

TABLE 2

LARGE SOLID-ROCKET MOTOR DIMENSIONS AND IGNITER CHARGE WEIGHTS

	Motor	Free Volume, $in.^3$	Increase, %	Surface Area, $in.^2$	Increase, %	Grain Length, in.	Increase, %	Igniter-Charge Weight, lb	Increase, %
1.	100 FW-1	632,000	10.0	107,500	0	422	31.0	6500	9.2
	100 FW-2	659,000		107,700		533		7100	
2.	100 FW-2	659,000	45.6	107,700	44.6	553	47.4	7100	69.0
	100 FW-3	960,000		155,700		815		12,000	
3.	100 FW-2	659,000	-28.5	107,700	-30.1	553	-23.7	7100	-29.6
	100 FW-4	471,000		75,300		422		5000	

TABLE 3

100 FW-4 MODEL 51 ALCLOJET IGNITER, BALLISTIC DESIGN

Main Charge Weight, W_I = 5000 gm

Pellet Selection, 360565

Pellet weight, w_p, = 50 gm

Pellet surface, a_s, = 6.56 in.^{2}

Number of Pellets Required, N: $N = \frac{W_I}{w_p} = \frac{5000}{50}$

$N = 100$

Total Surface Area, A_s: $A_s = Na_s = (100)(6.56)$

$A_s = 565$ in.^{2}

K ratio: K = 100 selected

K = 108 actual

Throat Area, A_t: $A_t = \frac{A_s}{K} = \frac{656}{100}$

$A_t = 6.56$ in.^{2}

A_t Actual - 6.1 in.^{2}

Free-flow area, A_f: A_f Actual - 61.5 in.^{2}

Maximum Expected Operating Pressure: 6000 psia

Average Expected Operating Pressure: 2000 psia

Average Burning Rate of Stoichiometric Alclo: 7.0 in./sec at 2000 psi

Expected Burning Duration: $\theta = \frac{t}{r} = \frac{0.37}{7}$

$\theta = 0.053$ sec

TABLE 4

100 FW-4 MODEL 52 ALCLOJET IGNITER, BALLISTIC DESIGN

Main Charge Weight, W_I = 8500 gm

Pellet Selection = 362842

Pellet weight, w_p, = 480 gm

Pellet surface, a_s, = 28.06 in.^{2}

Number of Pellets Required, N: $N = \frac{W_I}{w_p} = \frac{8500}{480}$

$N = 18$ (3 rows of 6 pellets each)

Total Surface Area, A_s: $A_s = Na_s = (18)(28.06)$

$A_s = 505$ in.^{2}

K ratio: K - 45 selected

K - 45.2 actual

Throat Area, A_t: $A_t = \frac{A_s}{k} = \frac{505}{45}$

$A_t = 11.25$ in.^{2}

A_t = actual = 11.18 in.^{2}

Free-flow Area, A_f: A_f actual = 31.4 in.^{2}

Maximum Expected Operating Pressure: 4000 psia

Average Expected Operating Pressure: 2000 psia

Average Burning Rate of 0-041 Alclo: 7.0 in./sec at 2000 psi

Expected Burning Duration: $\theta = \frac{t}{r} = \frac{.72}{7}$

$\theta = 0.103$ sec

Table 4

TABLE 5

100 FW-4 FREE-VOLUME CHAMBER TEST DATA

AFT-IGNITION PROGRAM

STATION & LOCATION FROM FORE-END	DATA MEASURED AT EACH STATION (COLUMN)	1	2	3	4
	IGNITER MODEL	MOD 51 FORE-END WITHOUT EXIT CONE TEST NO. 3	MOD 51 AFT-END WITH EXIT CONE TEST NO. 4	MOD 52 AFT-END WITH EXIT CONE TEST NO. 5	MOD 52 AFT-END WITHOUT EXIT CONE TEST NO. 6
FORE HEAD	MAXIMUM CHAMBER PRESSURE, PSIG	51.9	112.2	123	209
	TIME TO MAX CHAMBER PRESSURE, SEC	0.056	0.030	0.038	0.038
	TIME TO INITIAL CHAMBER PRESSURE RISE, SEC	0.005	0.026	0.031	0.035
#1 45-IN.	MAXIMUM CHAMBER PRESSURE, PSIG	49.2	67.8	102	91
	TIME TO MAX CHAMBER PRESSURE, SEC	0.056	0.032	0.041	0.042
	TIME TO INITIAL CHAMBER PRESSURE RISE, SEC	0.008	0.024	0.028	0.033
	PROPELLANT PATCH IGNITED	YES	NO	NO	NO
	CALORIMETER DATA, CAL/CM	37.1	NEGLIGIBLE	NEGLIGIBLE	NEGLIGIBLE
#2 110.5-IN.	MAXIMUM CHAMBER PRESSURE, PSIG	54.6	73.2	92	78
	TIME TO MAX CHAMBER PRESSURE, SEC	0.056	0.035	0.044	0.046
	TIME TO INITIAL CHAMBER PRESSURE RISE, SEC	0.012	0.022	0.024	0.031
	PROPELLANT PATCH IGNITED	YES	NO	NO	NO
	CALORIMETER DATA, CAL/CM^2	10.1	NEGLIGIBLE	NEGLIGIBLE	7.6
#3 187.4-IN.	MAXIMUM CHAMBER PRESSURE, PSIG	57.3	91.5	81	98
	TIME TO MAX CHAMBER PRESSURE, SEC	0.044	0.036	0.046	0.046
	TIME TO INITIAL CHAMBER PRESSURE RISE, SEC	0.017	0.017	0.021	0.028
	PROPELLANT PATCH IGNITED	YES	YES	YES	NO
	CALORIMETER DATA, CAL/CM^2	28.5	18.8	19.8*	10.6
#4 254.8-IN.	MAXIMUM CHAMBER PRESSURE, PSIG	50.2	75.0	74	67
	TIME TO MAX CHAMBER PRESSURE, SEC	0.043	0.038	0.050	0.058
	TIME TO INITIAL CHAMBER PRESSURE RISE, SEC	0.021	0.015	0.016	0.028
	PROPELLANT PATCH IGNITED	YES	YES	YES	YES
	CALORIMETER DATA, CAL/CM^2	16.8	20.7	20.5*	14.7
#5 327.8-IN.	MAXIMUM CHAMBER PRESSURE, PSIG	53.9	79.3	75	68
	TIME TO MAX CHAMBER PRESSURE, SEC	0.048	0.046	0.058	0.062
	TIME TO INITIAL CHAMBER PRESSURE RISE, SEC	0.026	0.012	0.012	0.021
	PROPELLANT PATCH IGNITED	YES	YES	YES	YES
	CALORIMETER DATA, CAL/CM^2	16.8	21.5	19.5*	17.2
#6 395.6-IN.	MAXIMUM CHAMBER PRESSURE, PSIG	50.8	70.2	68	76
	TIME TO MAX CHAMBER PRESSURE, SEC	0.040	0.052	0.056	0.055
	TIME TO INITIAL CHAMBER PRESSURE RISE, SEC	0.028	0.008	0.008	0.018
	PROPELLANT PATCH IGNITED	YES	YES	YES	YES
	CALORIMETER DATA, CAL/CM^2	20.0	24.8	18.8*	18.1

*CORRECTED CALORIMETRIC DATA; THE VALUES REPORTED IN THE SECOND TECHNICAL NOTE, REPORT NO. SSD-TDR-62-47, WERE IN ERROR.

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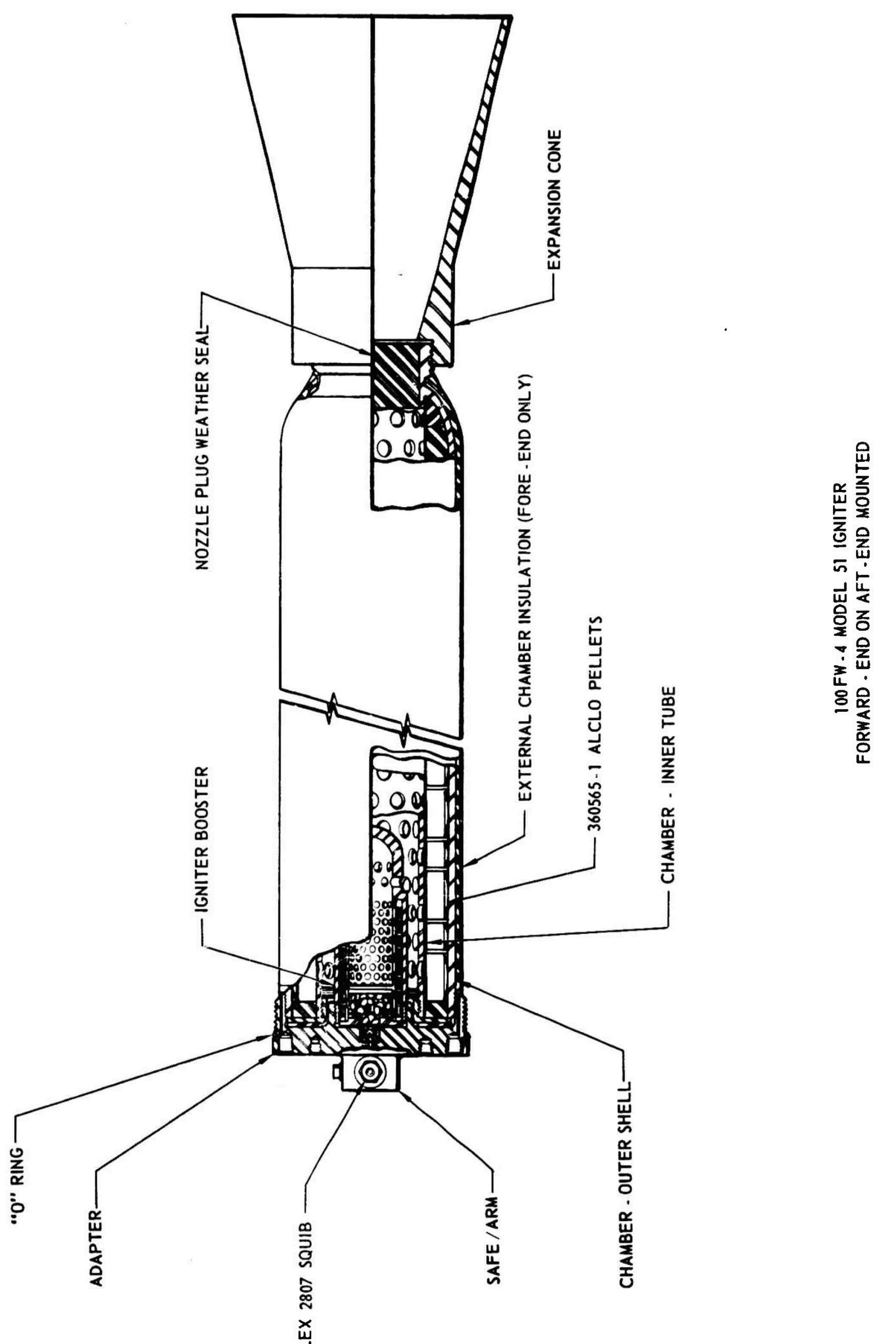
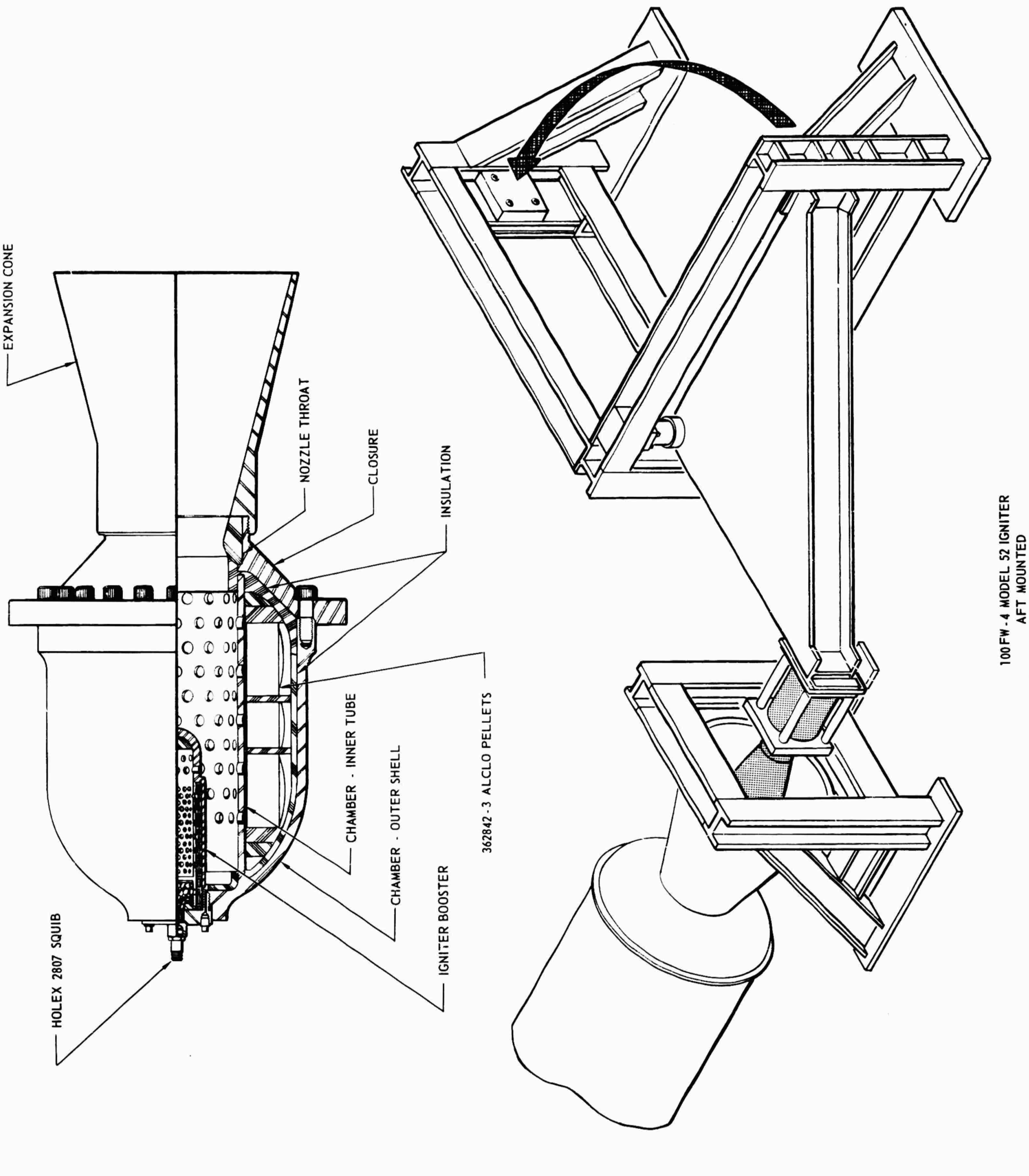


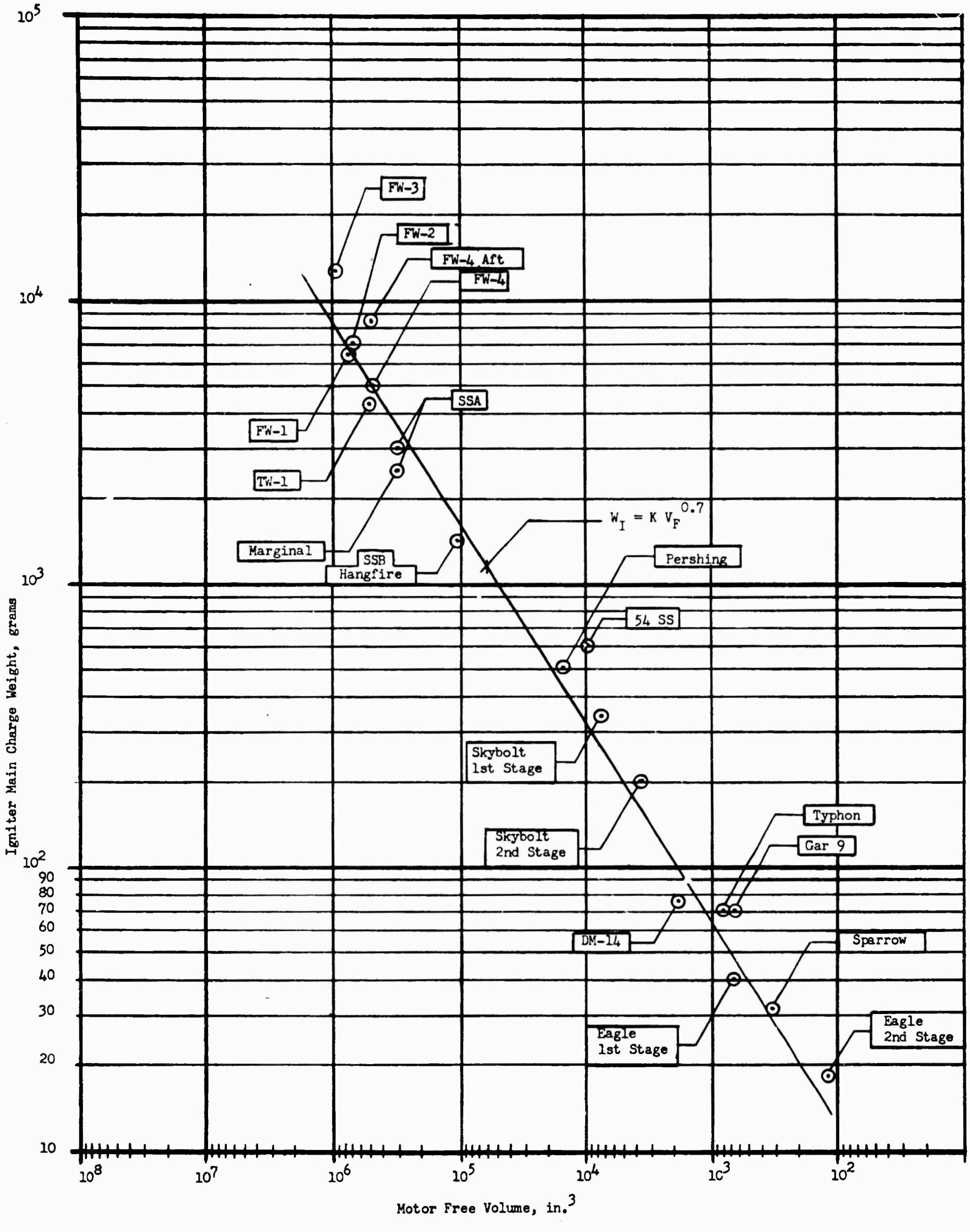
100 FW-4 Model 51 Igniter

Figure 1



100 FW-4 Model 52 Igniter

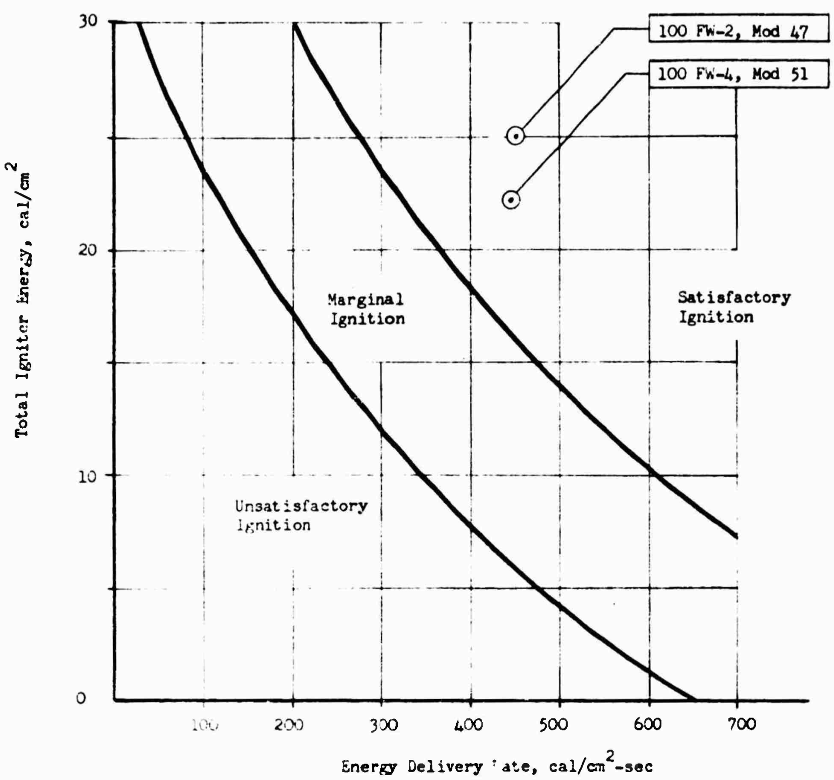
Figure 2



Igniter Charge Weight vs Motor Free-Volume

Figure 3

TOTAL IGNITER ENERGY VS ENERGY DELIVERY RATE CURVE



Total Energy and Energy Delivery Rate
For Igniter 100 FW-4, Model 51

Total Energy:

5000 (Main Charge, gms) x 2.18 (Alclo Energy, Kilocal/gm) = 10.9×10^6 Calories
75,300 (100 FW-4 Surface Area, in.^{2}) x 6.54 Conversion, cm^2) = 0.492×10^6 cm^2

$$\text{Total Energy} = \frac{10.9 \times 10^6}{0.492 \times 10^6} = 22.2 \text{ cal/cm}^2$$

Energy Delivery Rate:

Igniter Duration = 0.050 sec

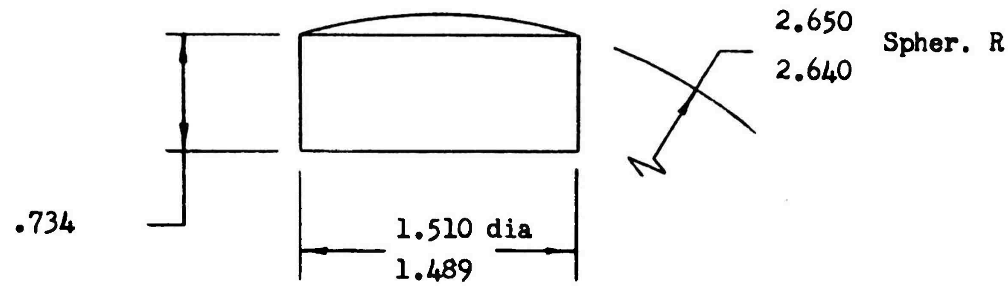
$$\text{Energy Delivery Rate} = \frac{22.2}{0.050} = 445 \text{ cal/cm}^2 - \text{sec}$$

100 FW-4 Model 51 Igniter Main-Charge-Energy Evaluation

Figure 4

Pellet 360565-1

Stoichiometric Alclo

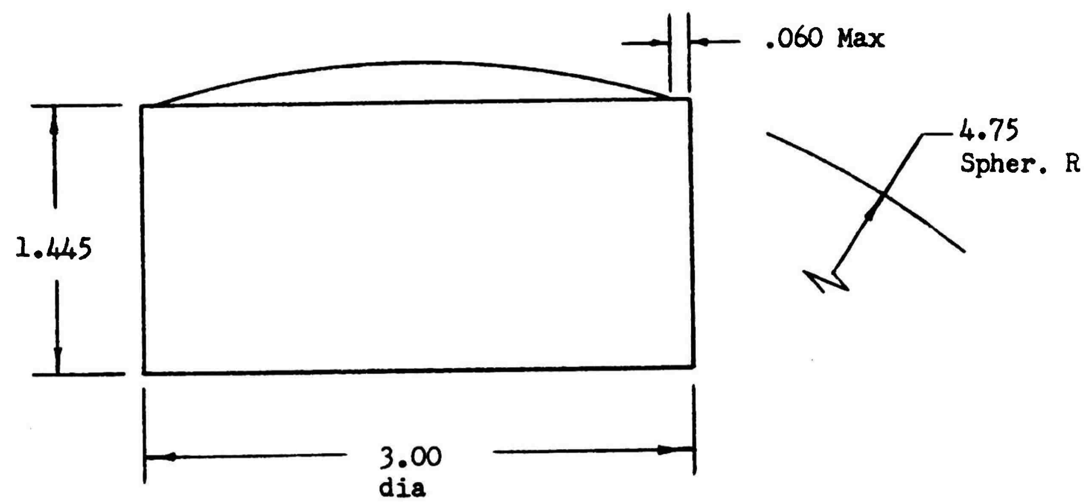


Pellet Surface Area, a = 6.56 in.^{2}
Pellet Weight, w_p = 50^{8}grams
Pellet Web, t = 0.37 inches

Pellet 362842-3

A30-I4.6-L6.0 Alclo

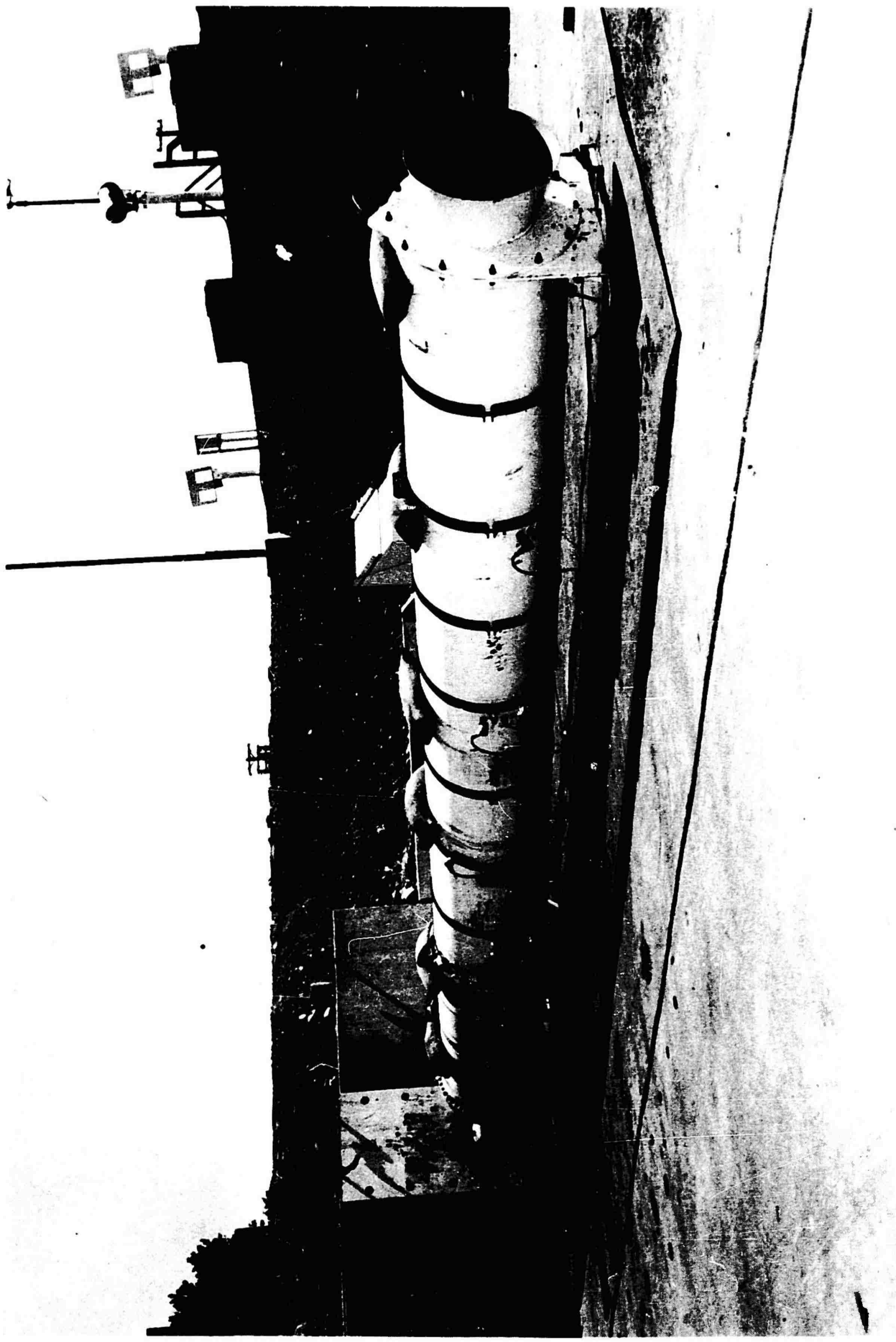
Type 0-041



Pellet Surface Area, a_s = 28.06 in.^{2}
Pellet Weight, w_p = 480 $\pm$ 10 grams
Pellet Web, t = 0.72 inches

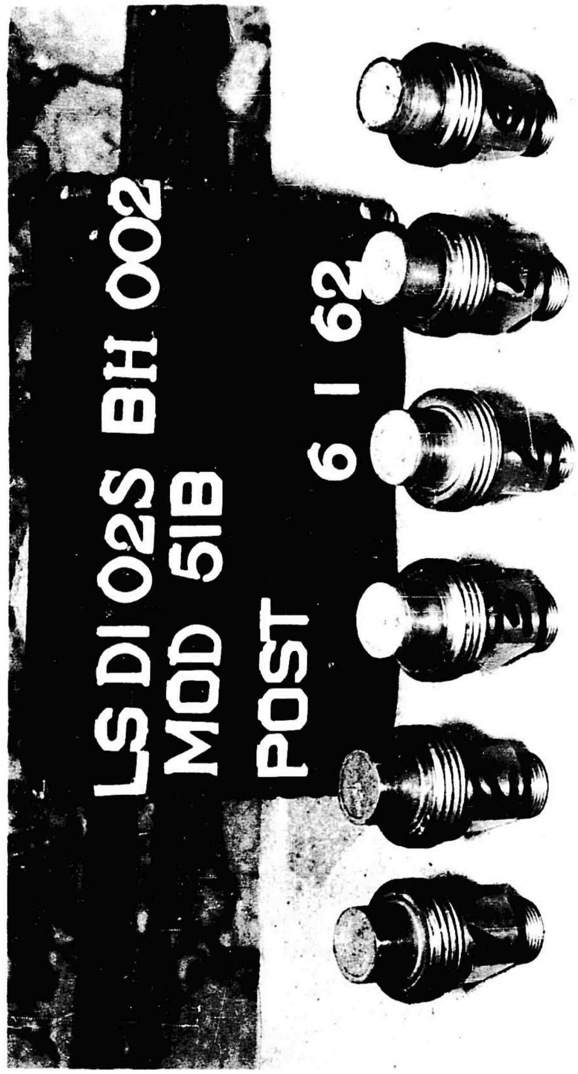
Alclo Pellets for Aft-Ignition Program

Figure 5



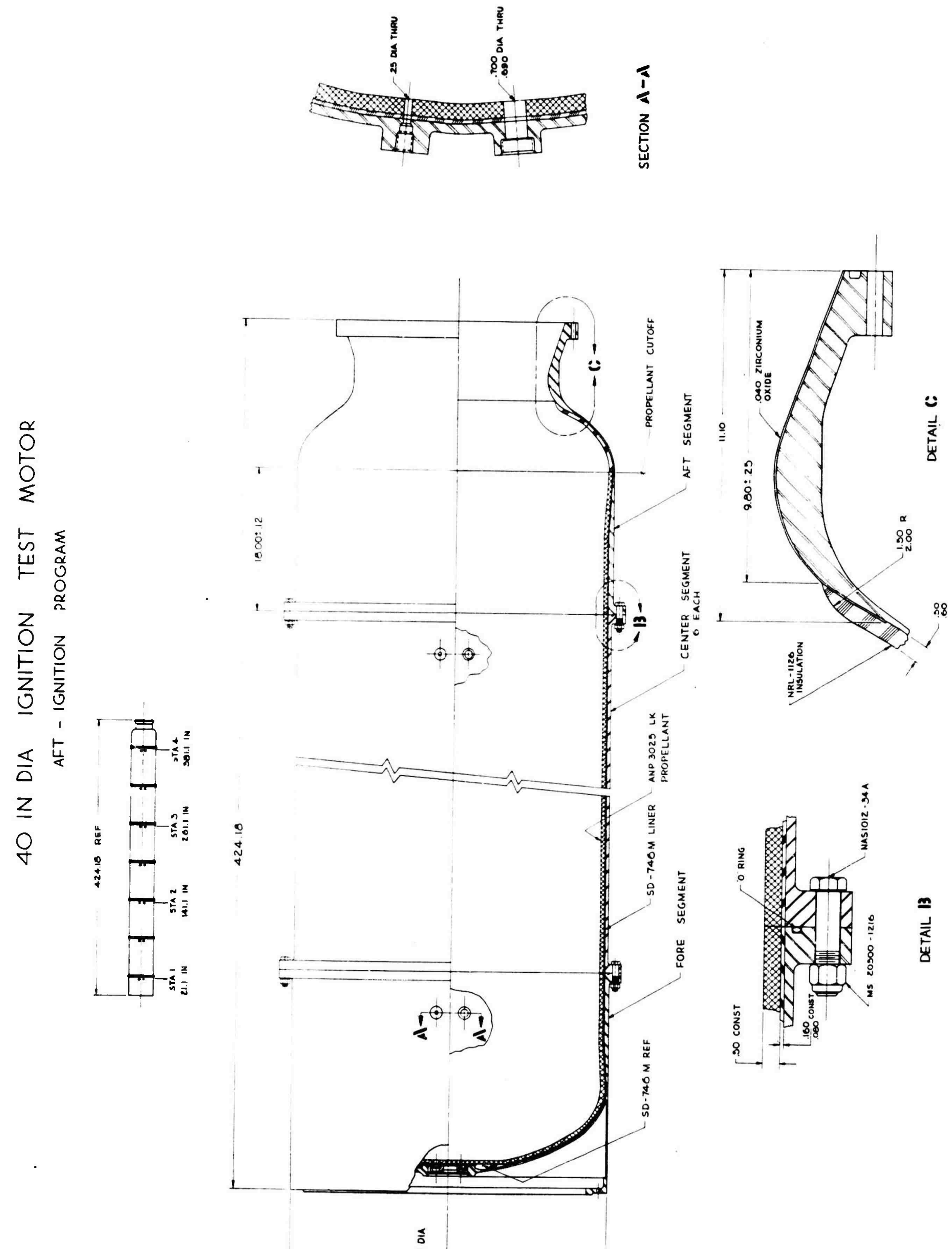
Free-Volume Test Chamber, Motor 100 FW-4 (Photo 6-62S 13817)

Figure 6



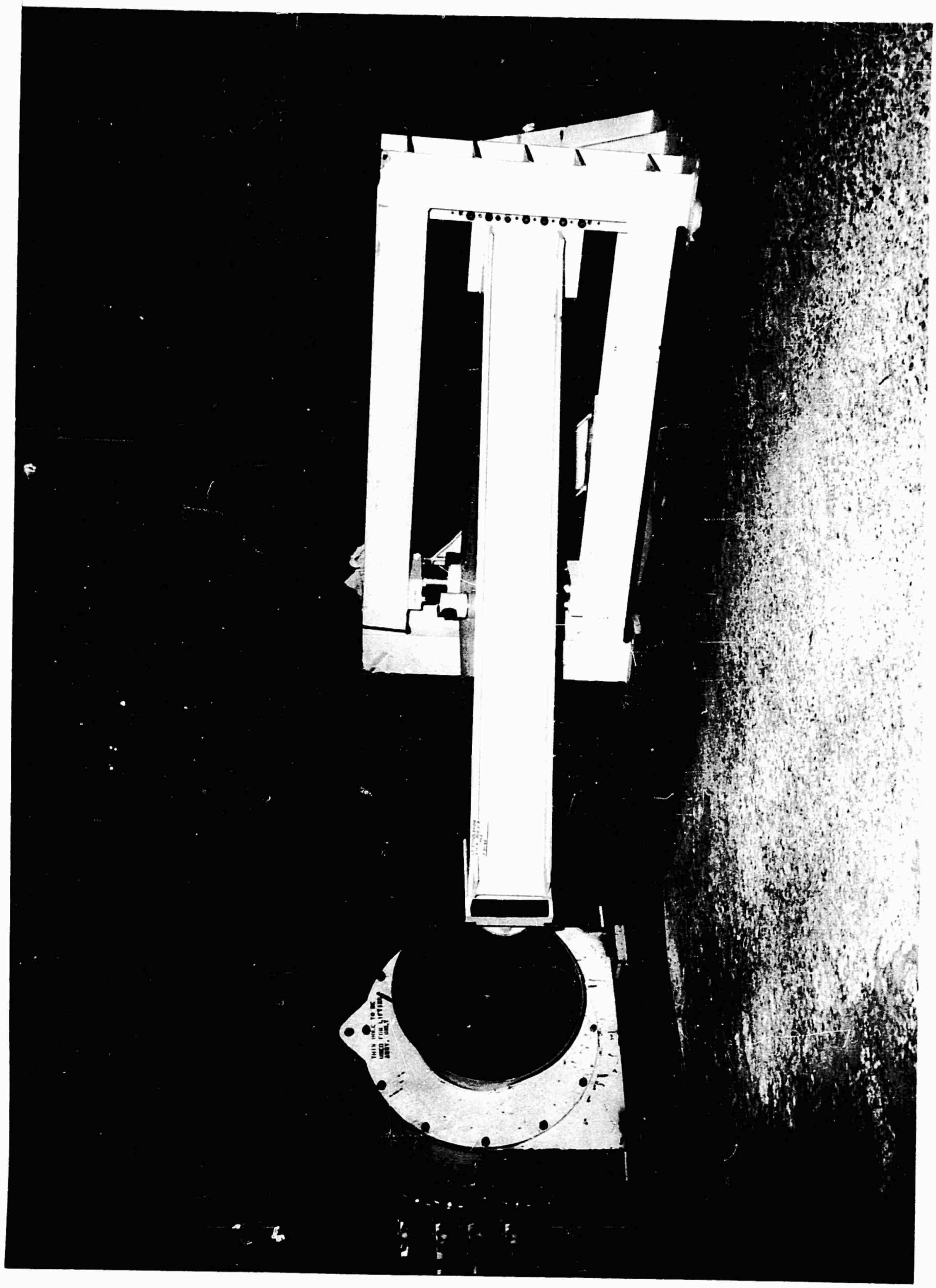
Propellant Patches for Free-Volume Test Chamber (Photo 6-62S 13915)

Figure 7



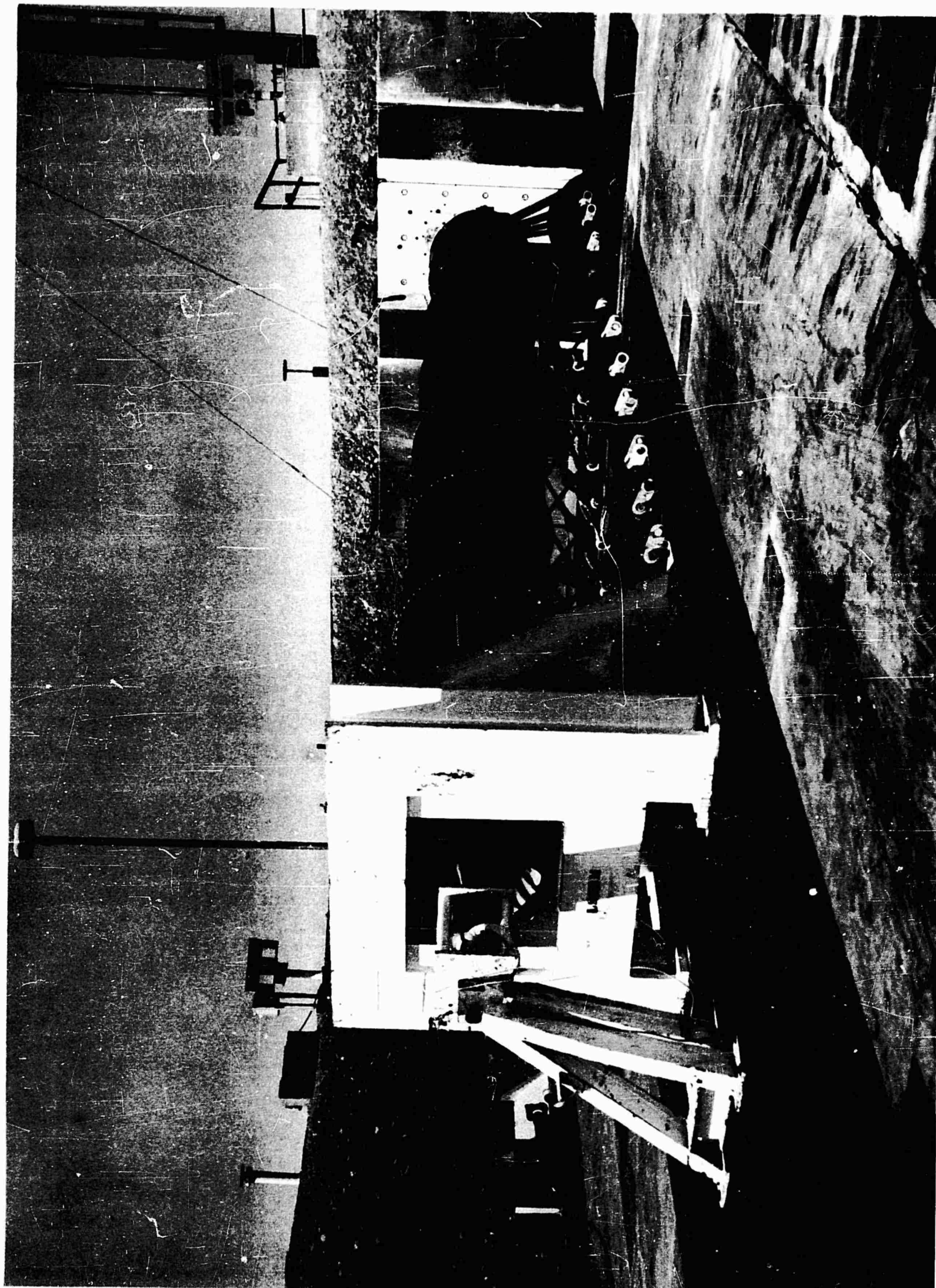
40-in.-dia Ignition-Test Motor

Figure 8



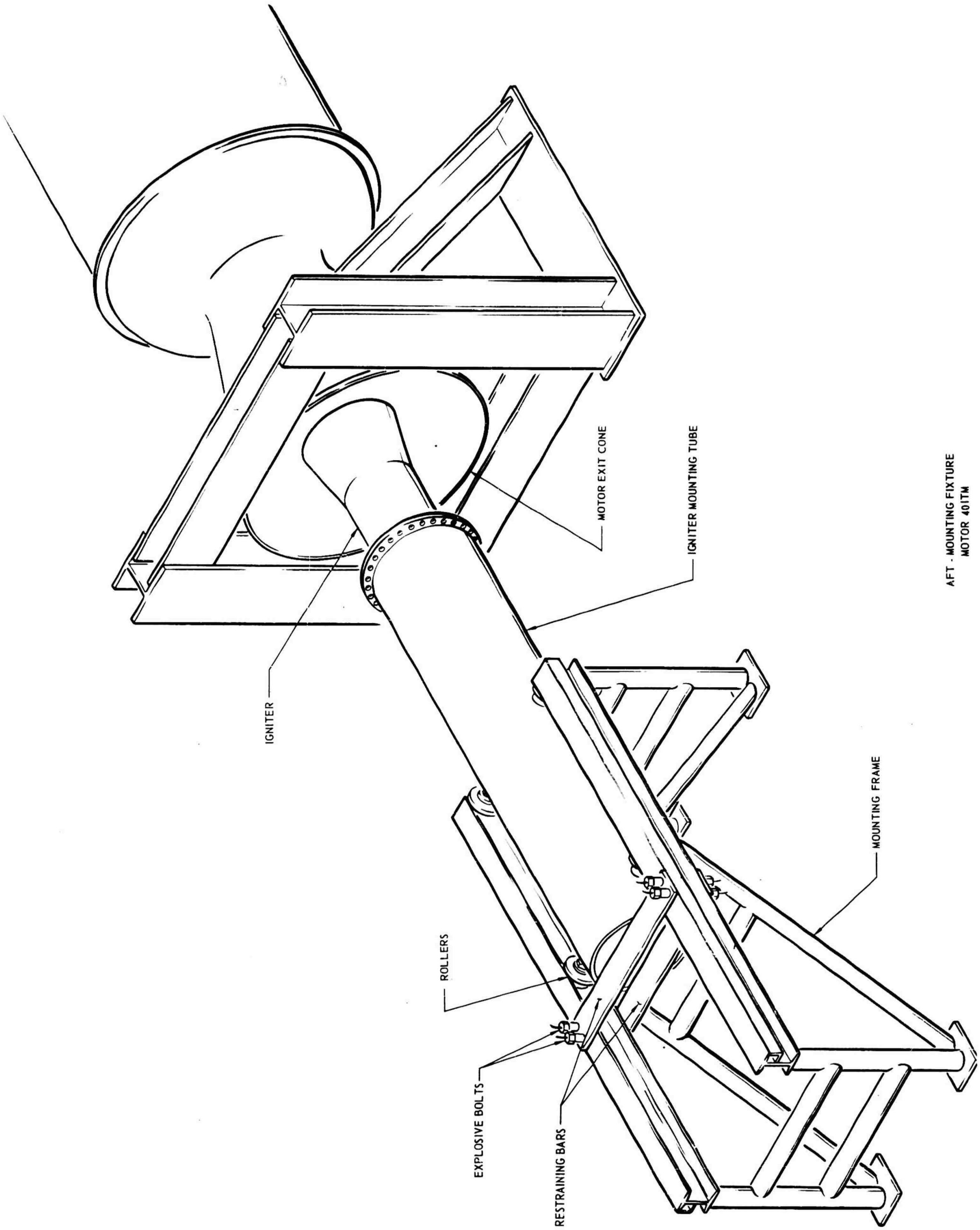
Aft Mounted Fixture, Free-Volume Chamber Tests (Photo 6-62S 13920)

Figure 9



Aft Mounted Fixture, Motor 40 ITM-1 (Photo 7-62S 17100)

Figure 10



Aft Mounted Fixture, Motor 40 ITM-2

Figure 11

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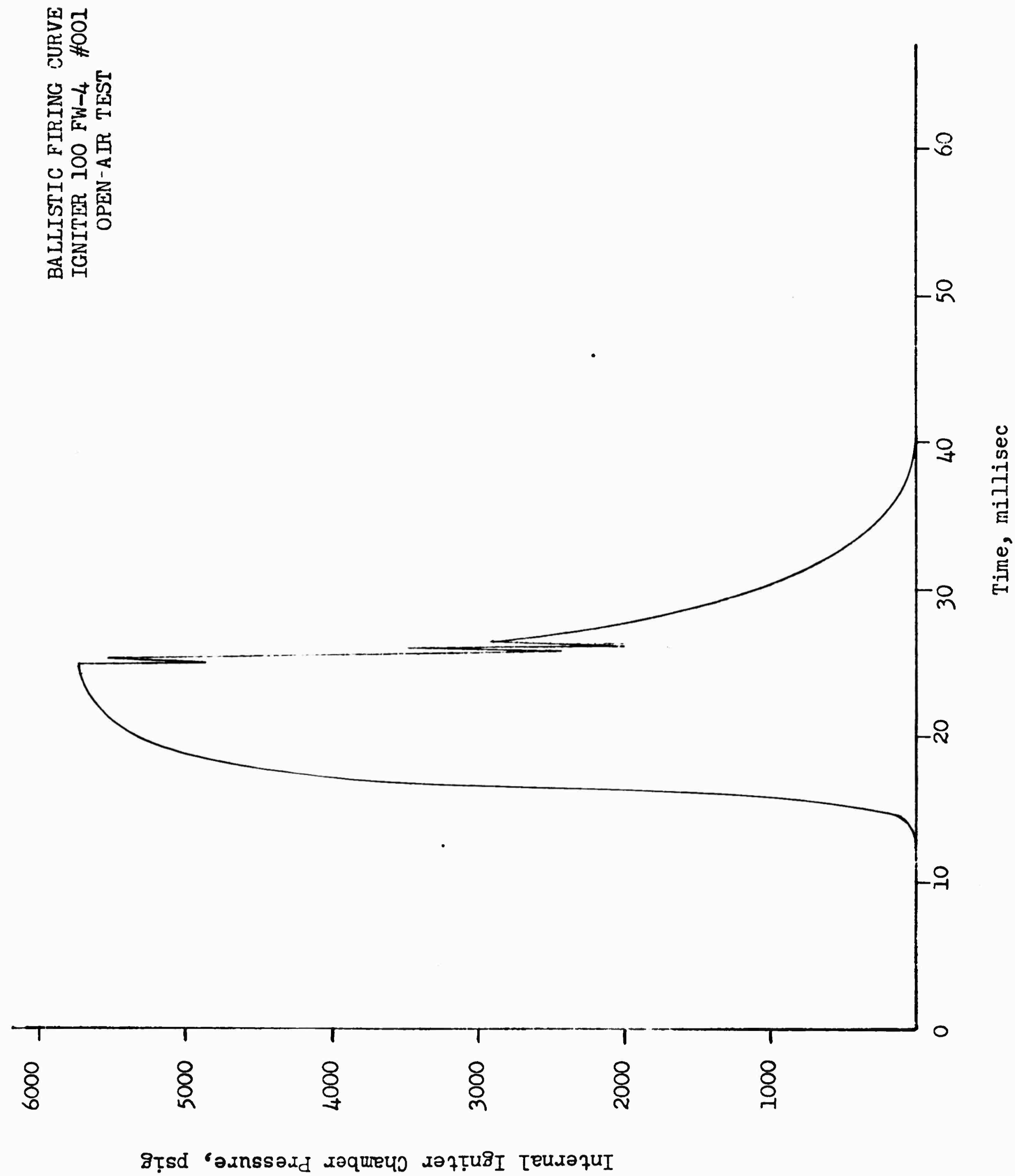
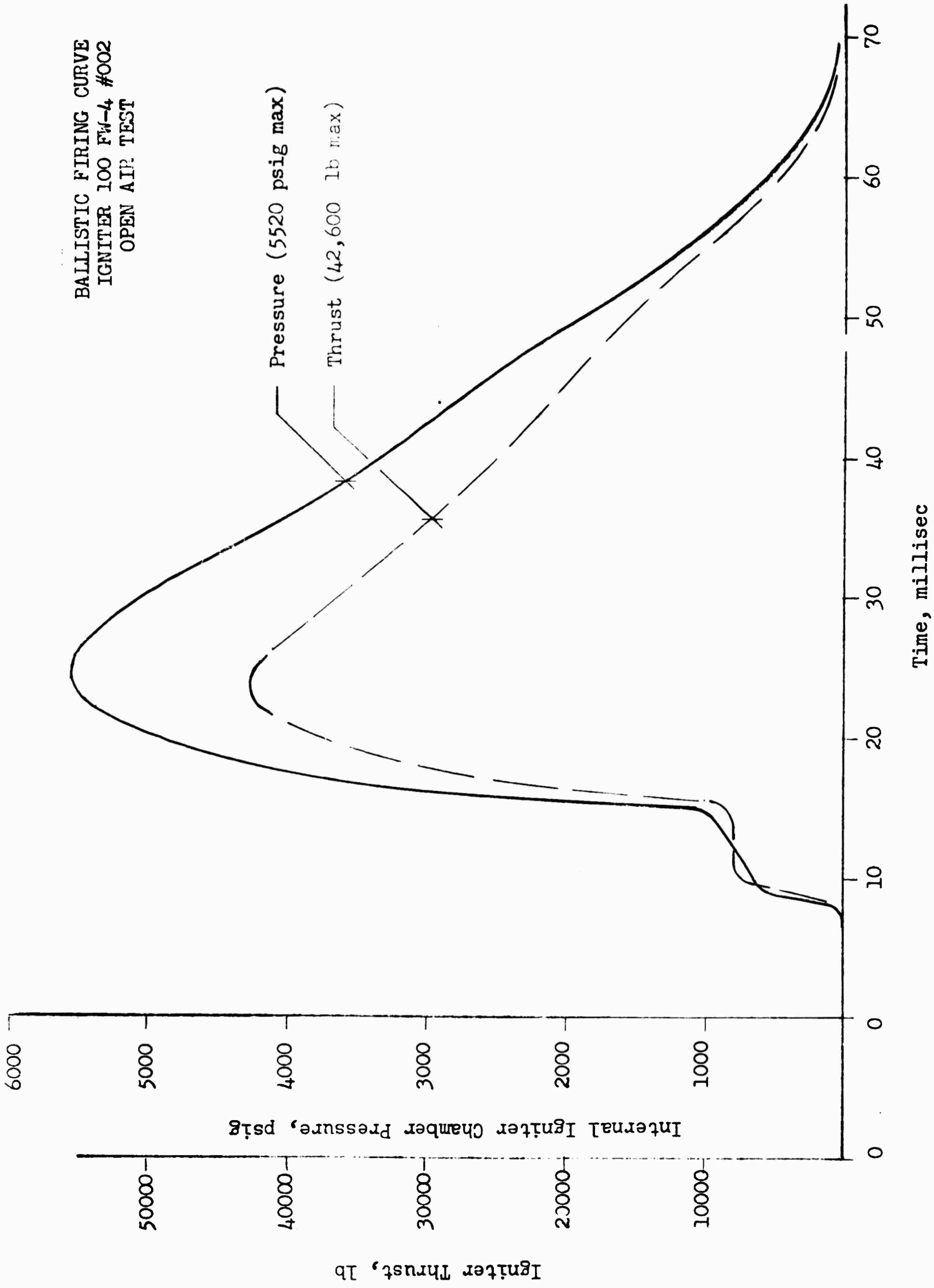
Typical Igniter Open-Air Test Arrangement (Photo 6-62S 14147)

Figure 12



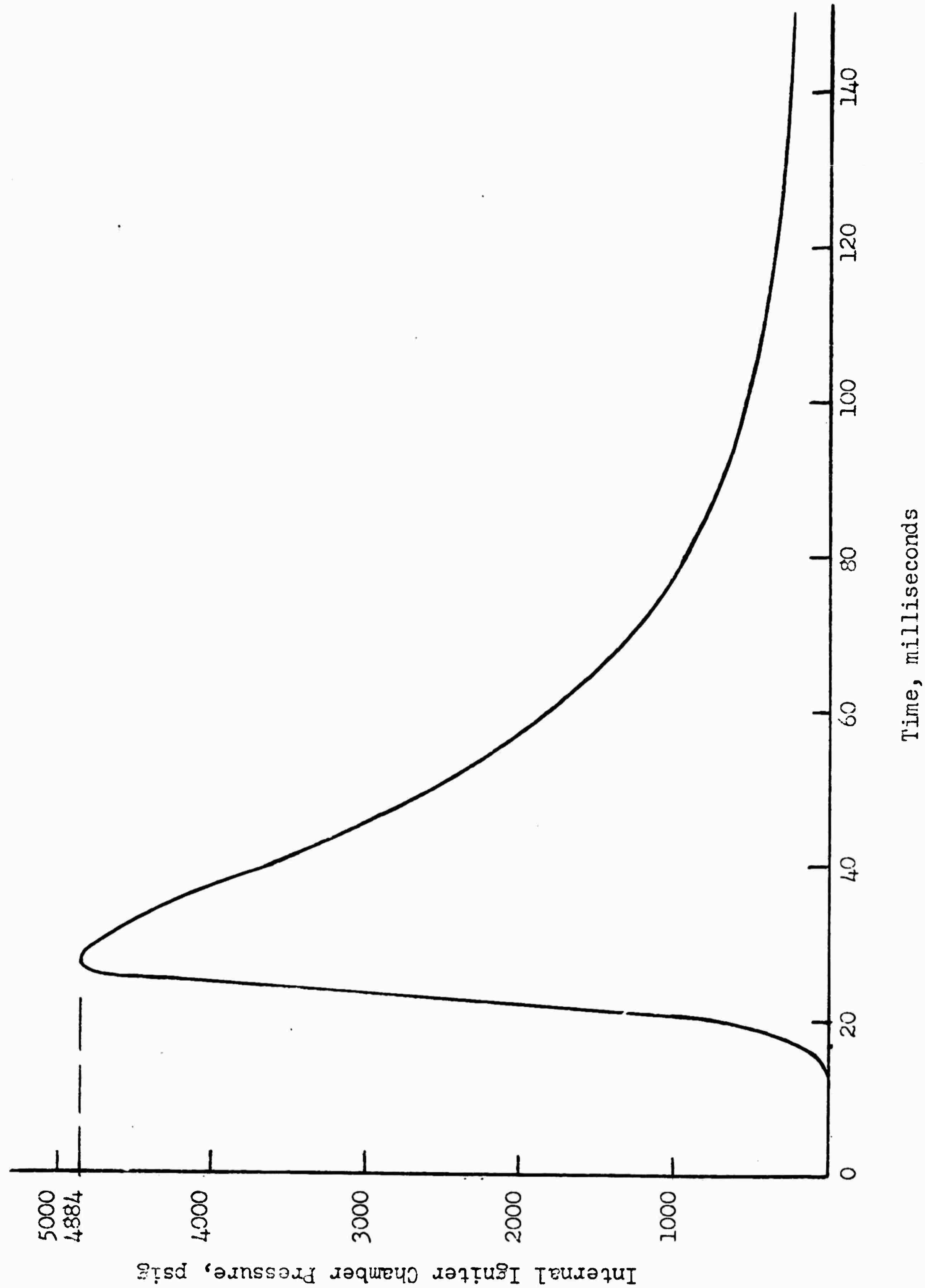
Igniter Performance, Model 51, Test No. 1

Figure 13



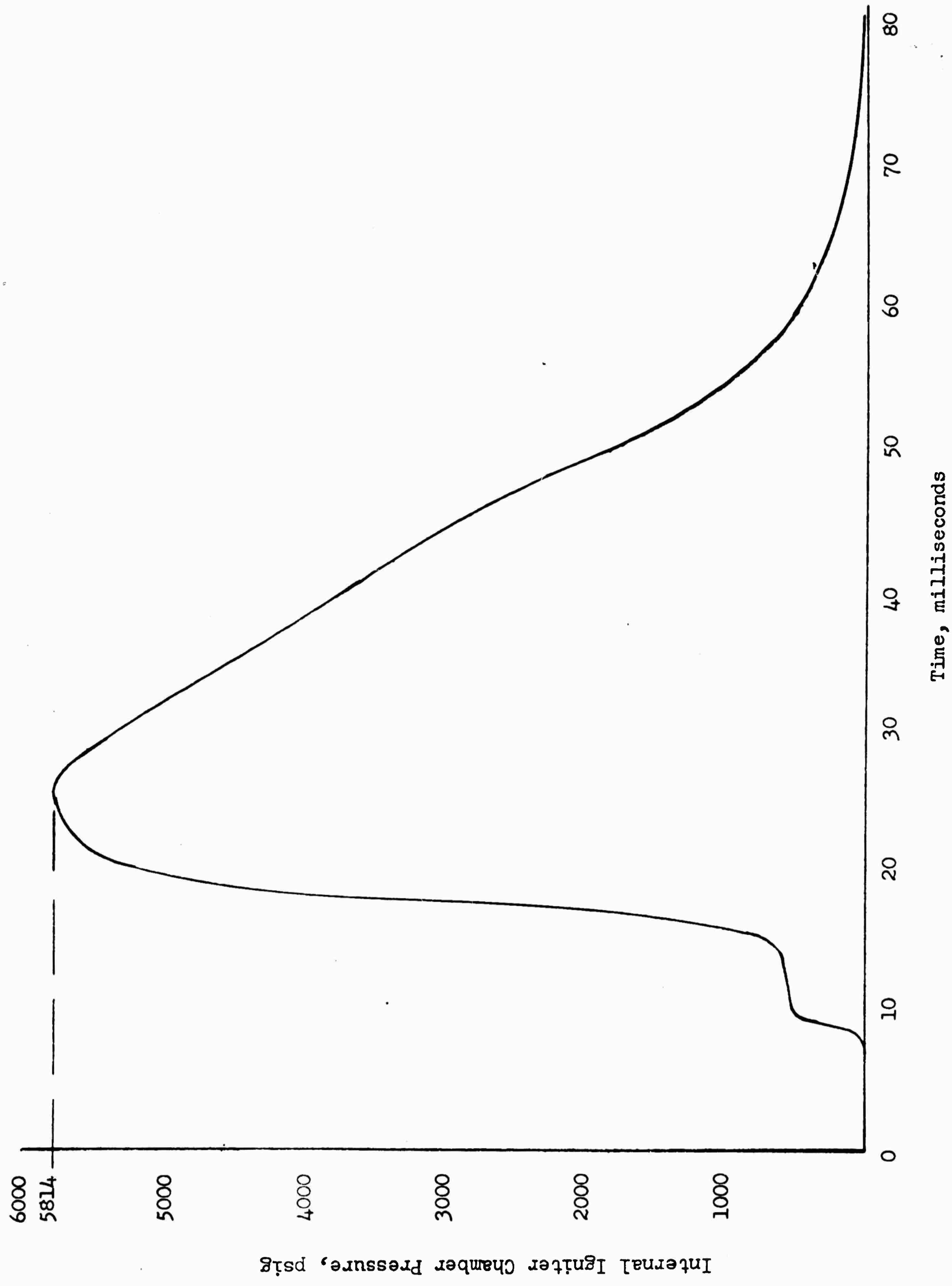
Igniter Performance, Model 51, Test No. 1A

Figure 14



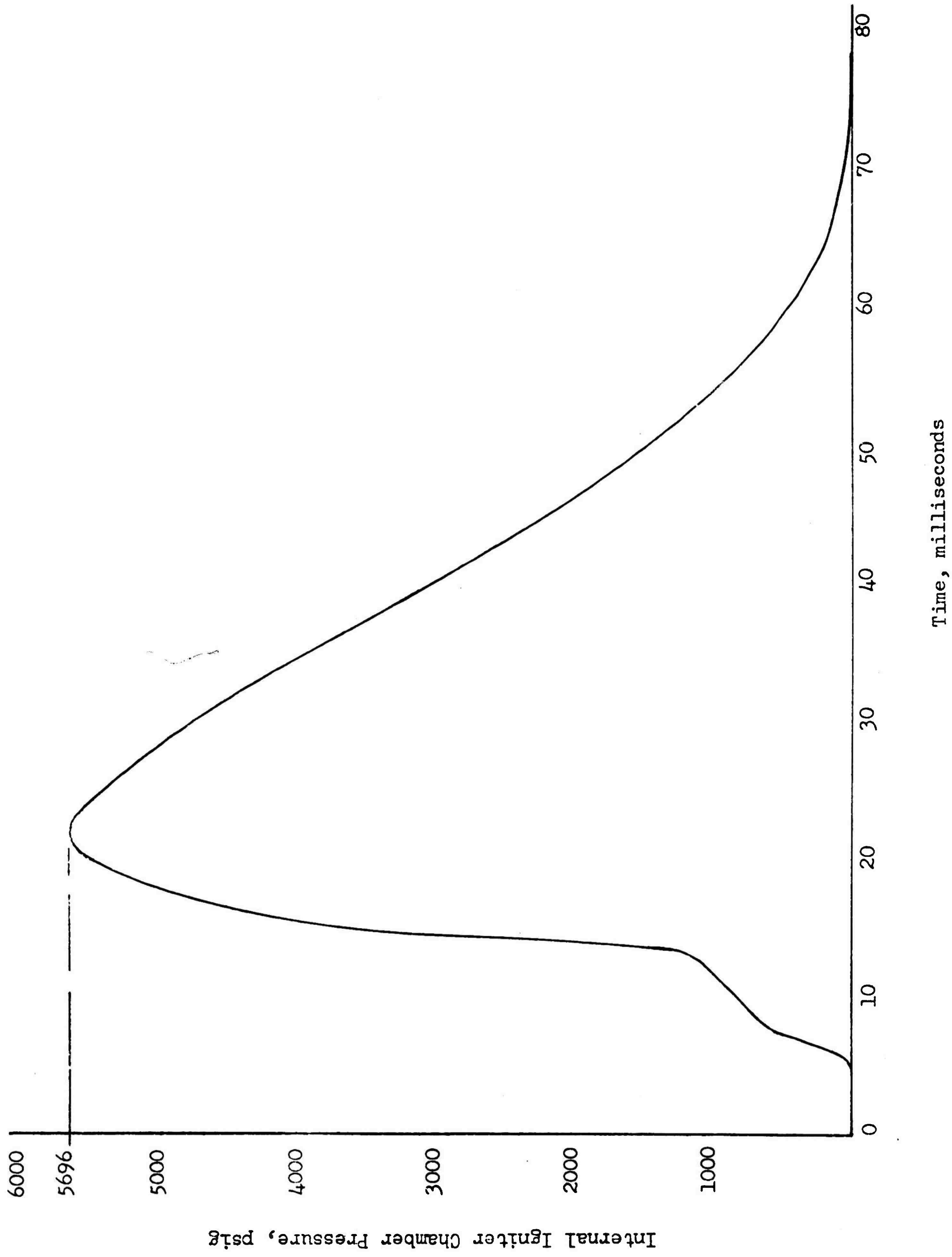
Igniter Performance, Model 52, Test No. 2

Figure 15



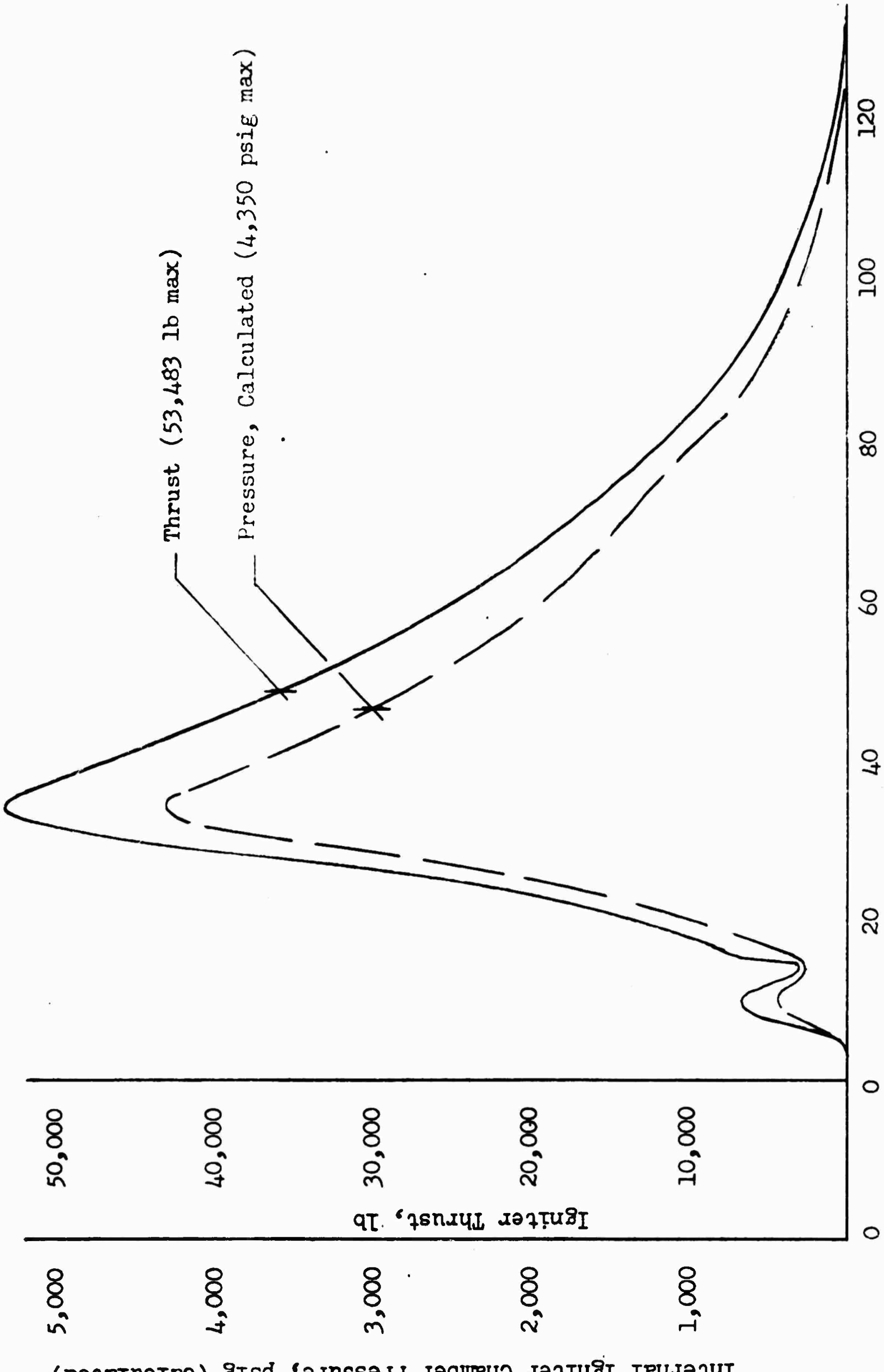
Igniter Performance, Model 51, Test No. 3

Figure 16



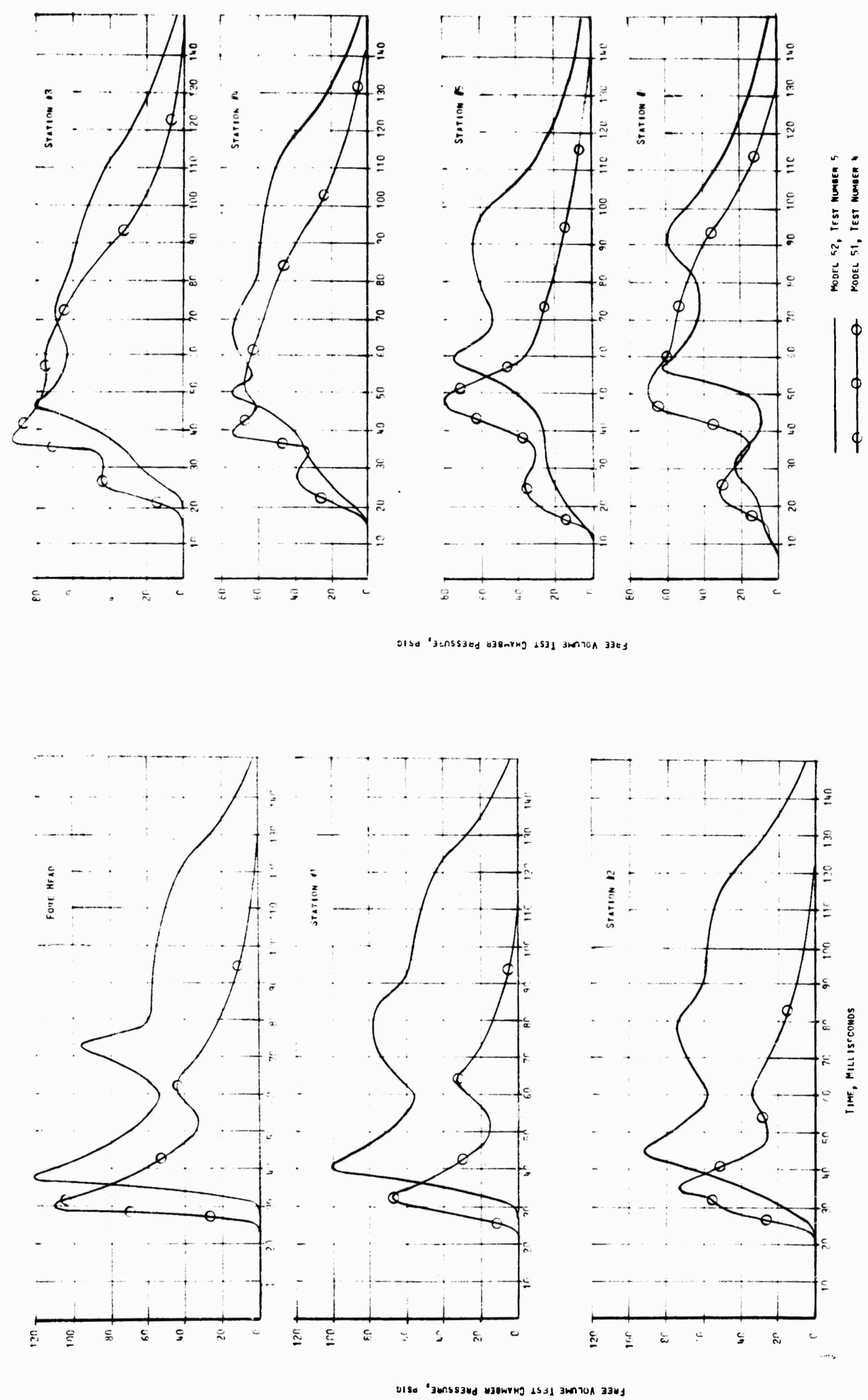
Igniter Performance, Model 51, Test No. 4

Figure 17



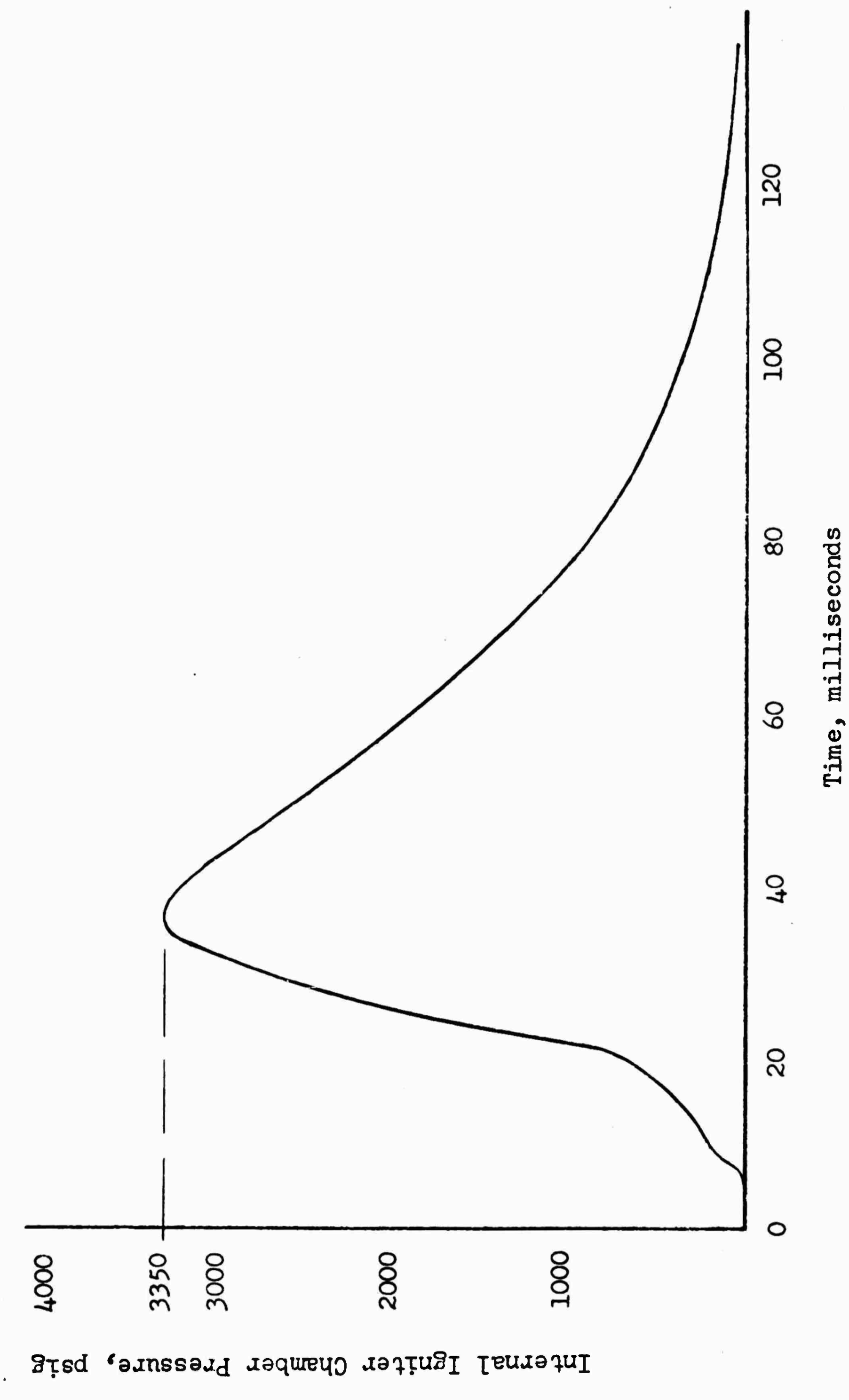
Igniter Performance, Model 52, Test No. 5

Figure 18



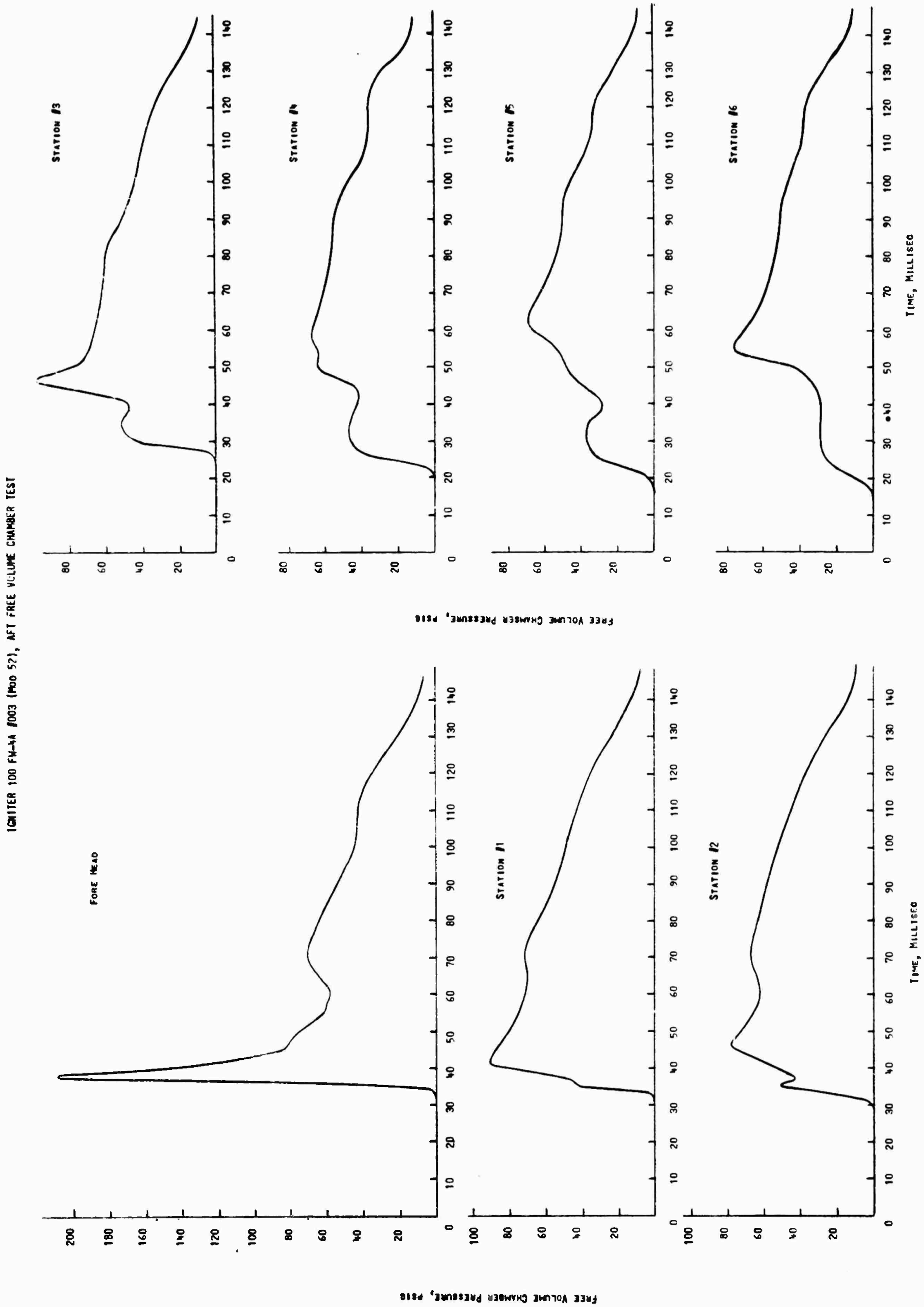
Free-Volume Chamber Pressure Data, Tests No. 4 and 5

Figure 19



Igniter Performance, Model 52, Test No. 6

Figure 20



Free-Volume Chamber Pressure Data, Test No. 6

Figure 21

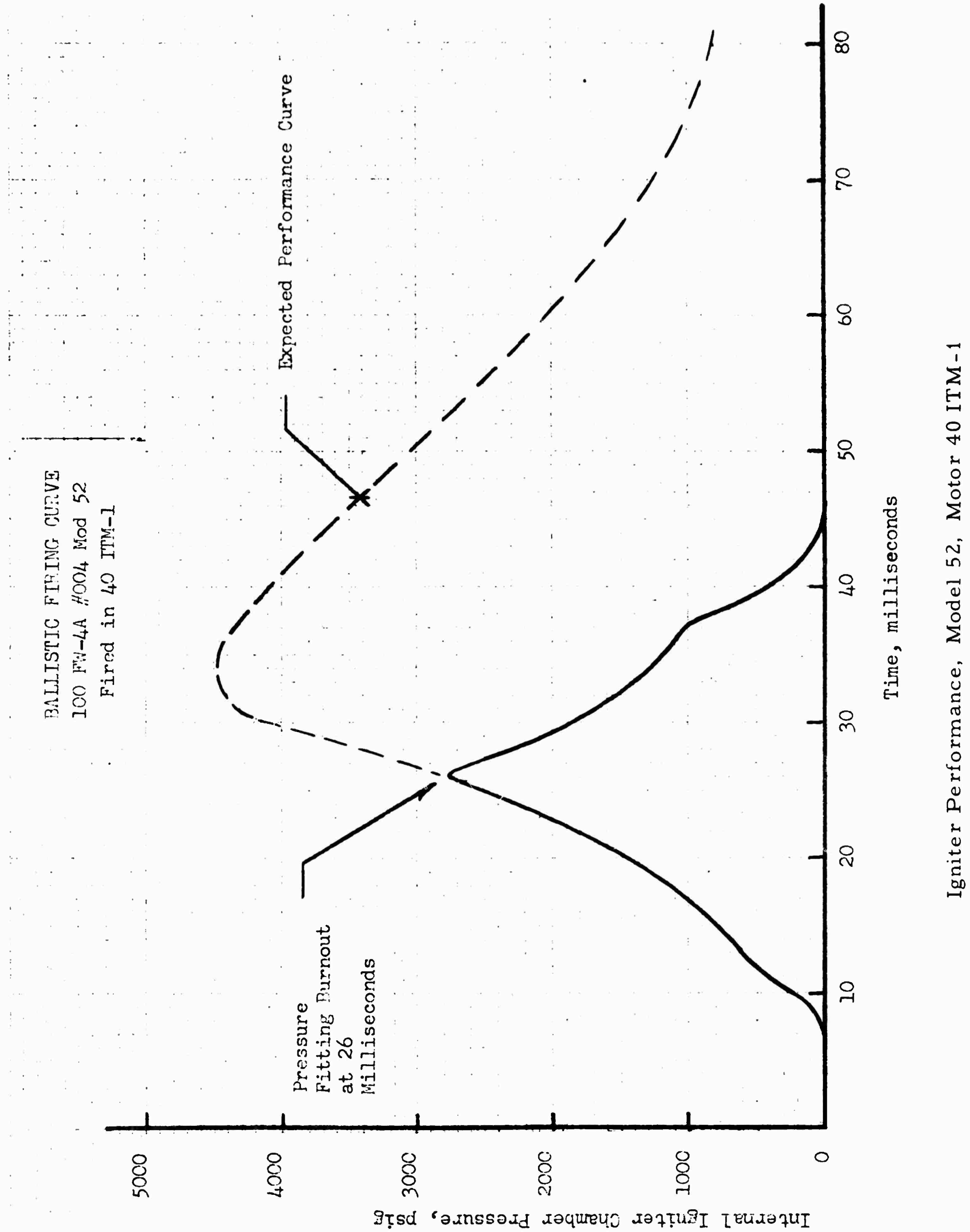
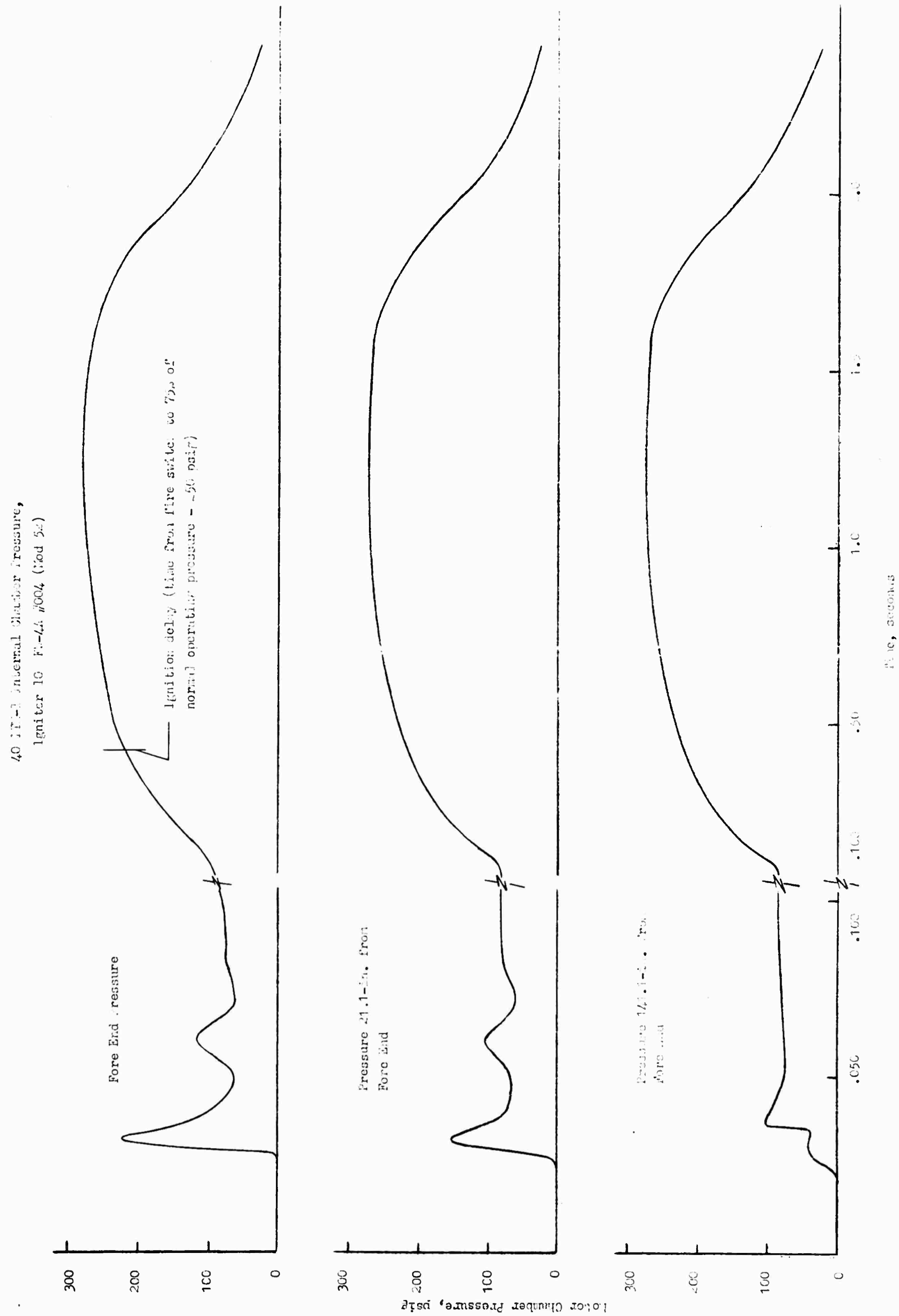

BALLISTIC FIRING CURVE
100 FW-4A #004 Mod 52
Fired in 40 ITM-1
Expected Performance Curve
Pressure
Fitting Burnout
at 26
Milliseconds
Internal Igniter Chamber Pressure, psig
0
1000
2000
3000
4000
5000
10
20
30
40
50
60
70
80
Time, milliseconds
Igniter Performance, Model 52, Motor 40 ITM-1

Figure 22



Motor Performance Curve, 40 ITM-1

Figure 23, Sheet 1 of 2

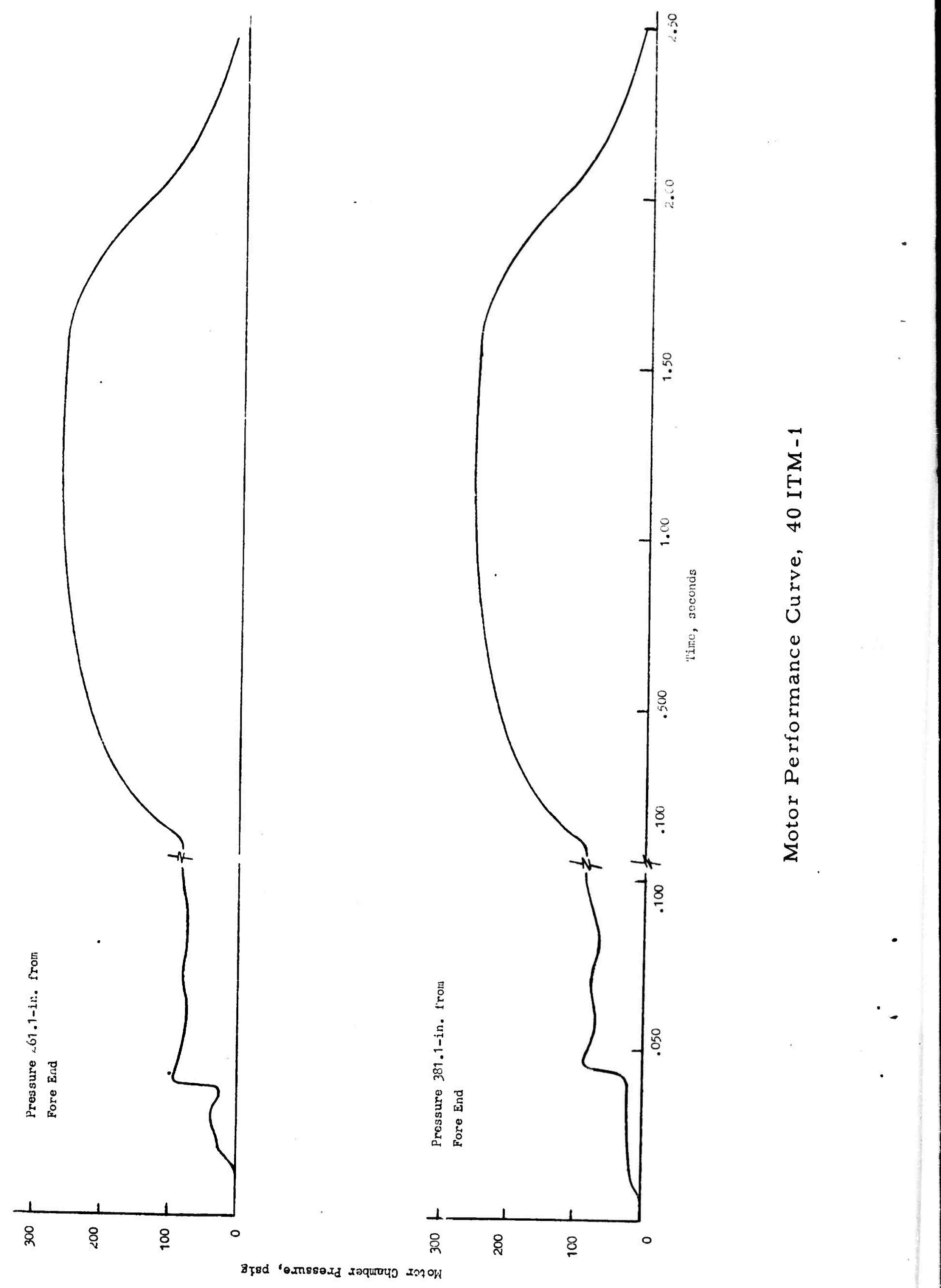
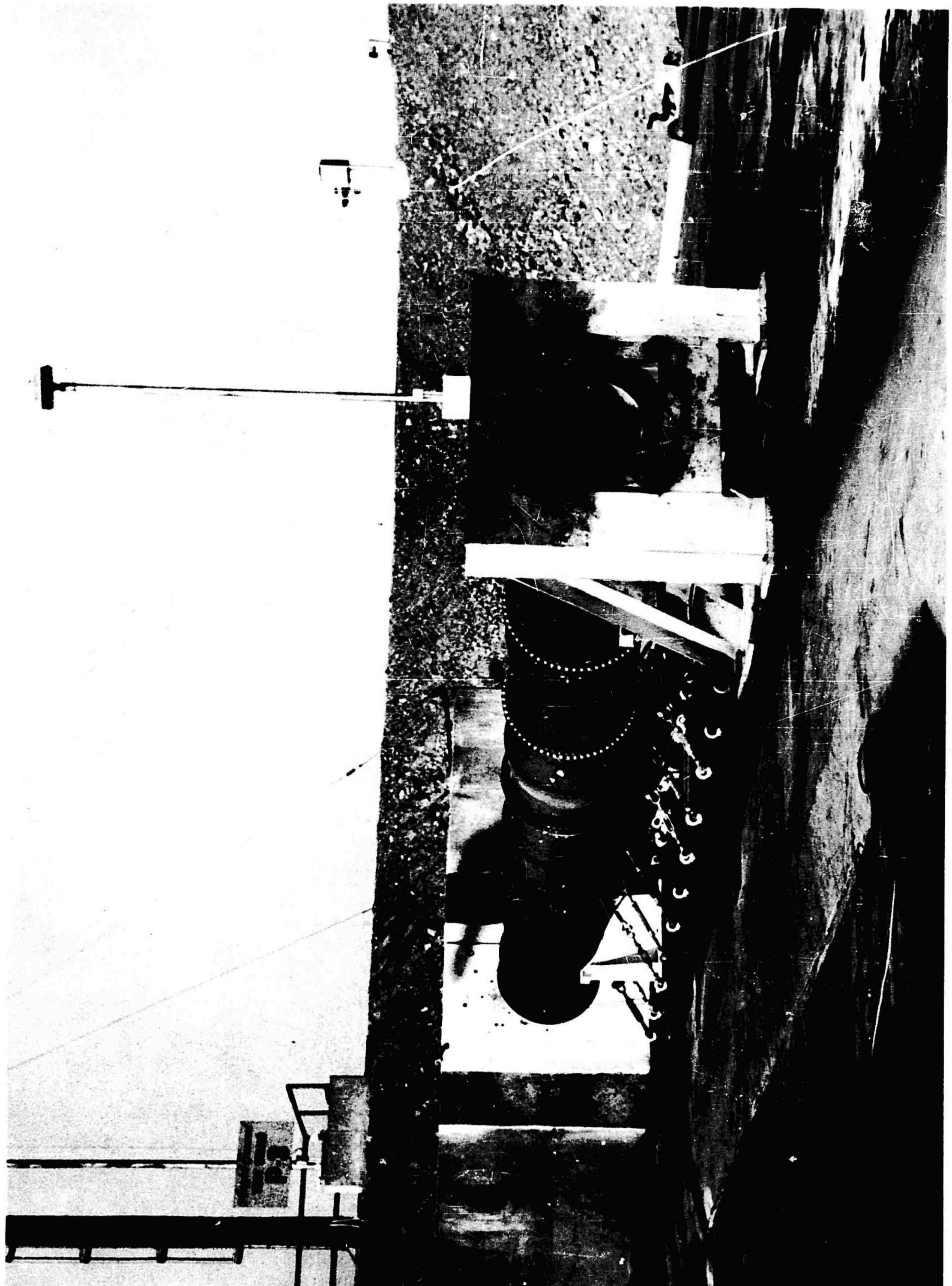
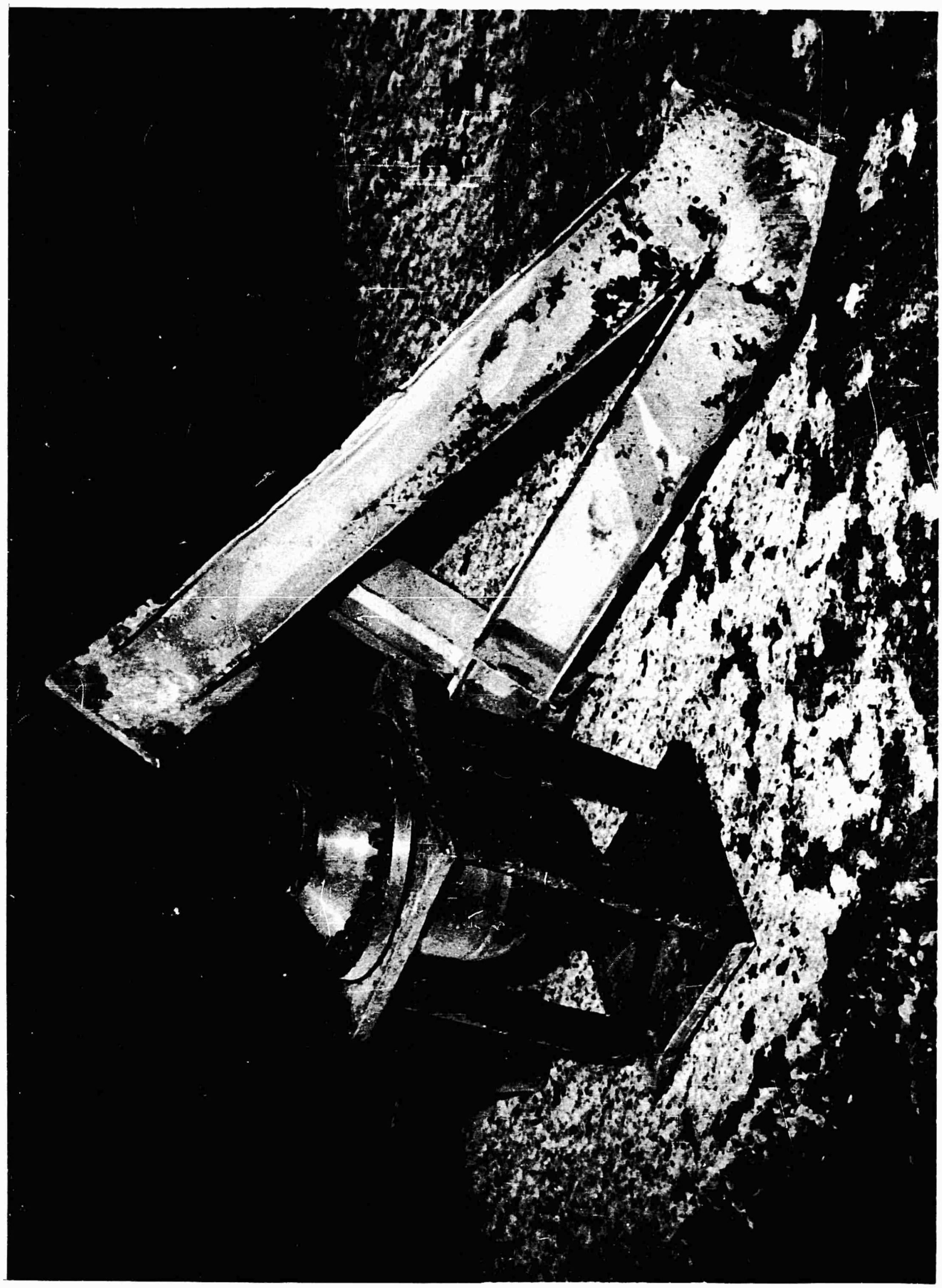


Figure 23, Sheet 2 of 2



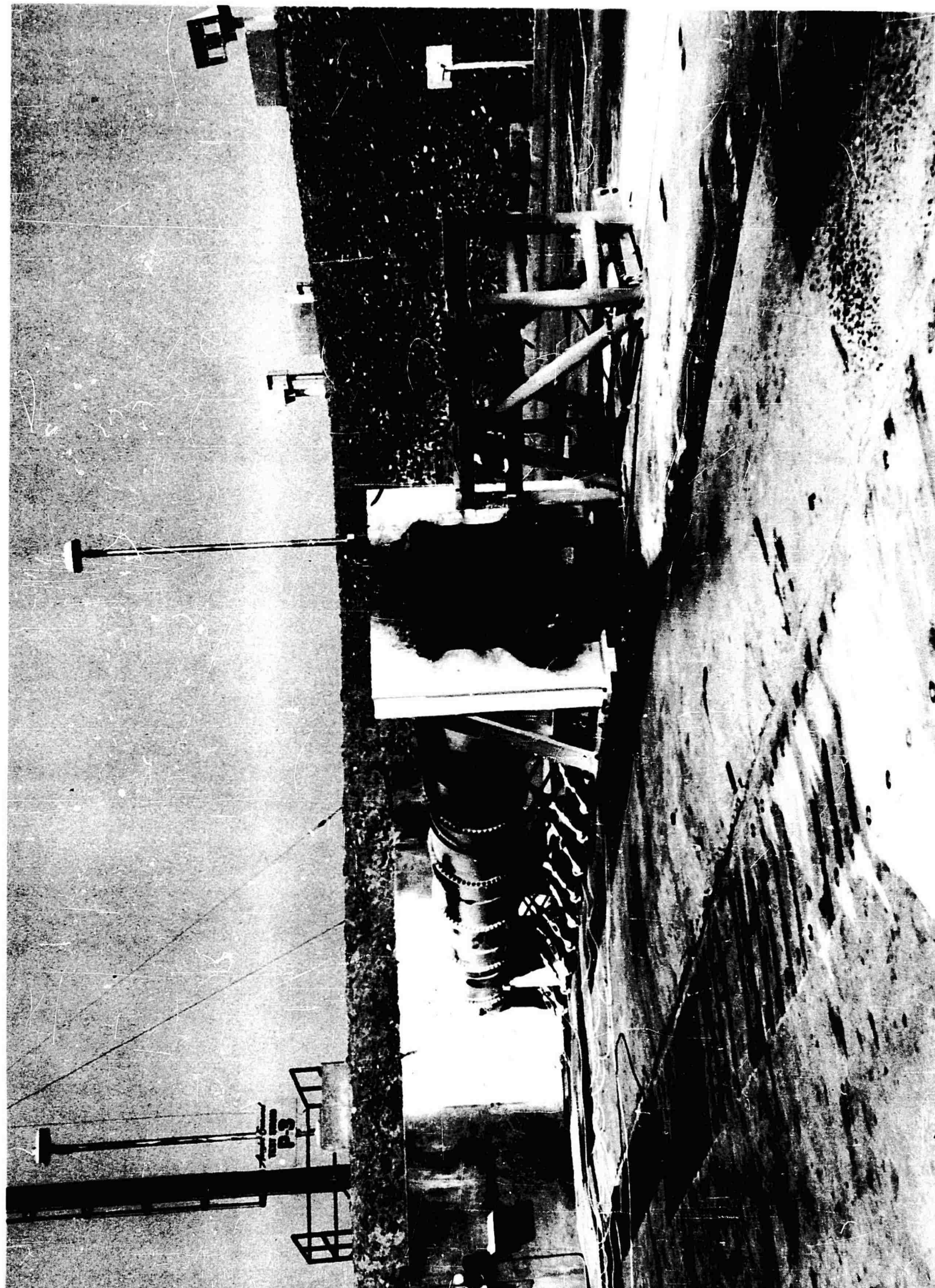
Postfiring View, Motor 40 ITM-1 (Photo 7-62S 17108)

Figure 24



Postfiring View, Igniter and Mounting Fixture, Motor 40 ITM-1
(Photo 7-62S 17105)

Figure 25



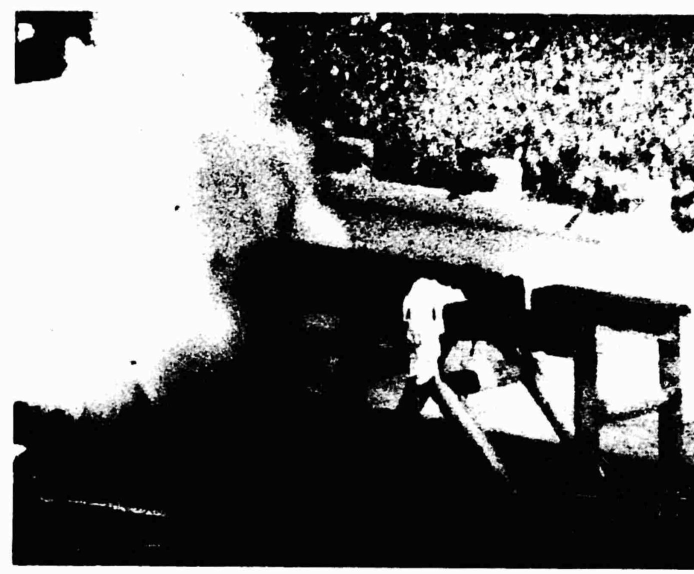
Postfiring View, Motor 40 ITM-2 (Photo 7-62S 18361)

Figure 26

Igniter Functioning, t=0.020 sec

Fire Switch, t=0.0 sec

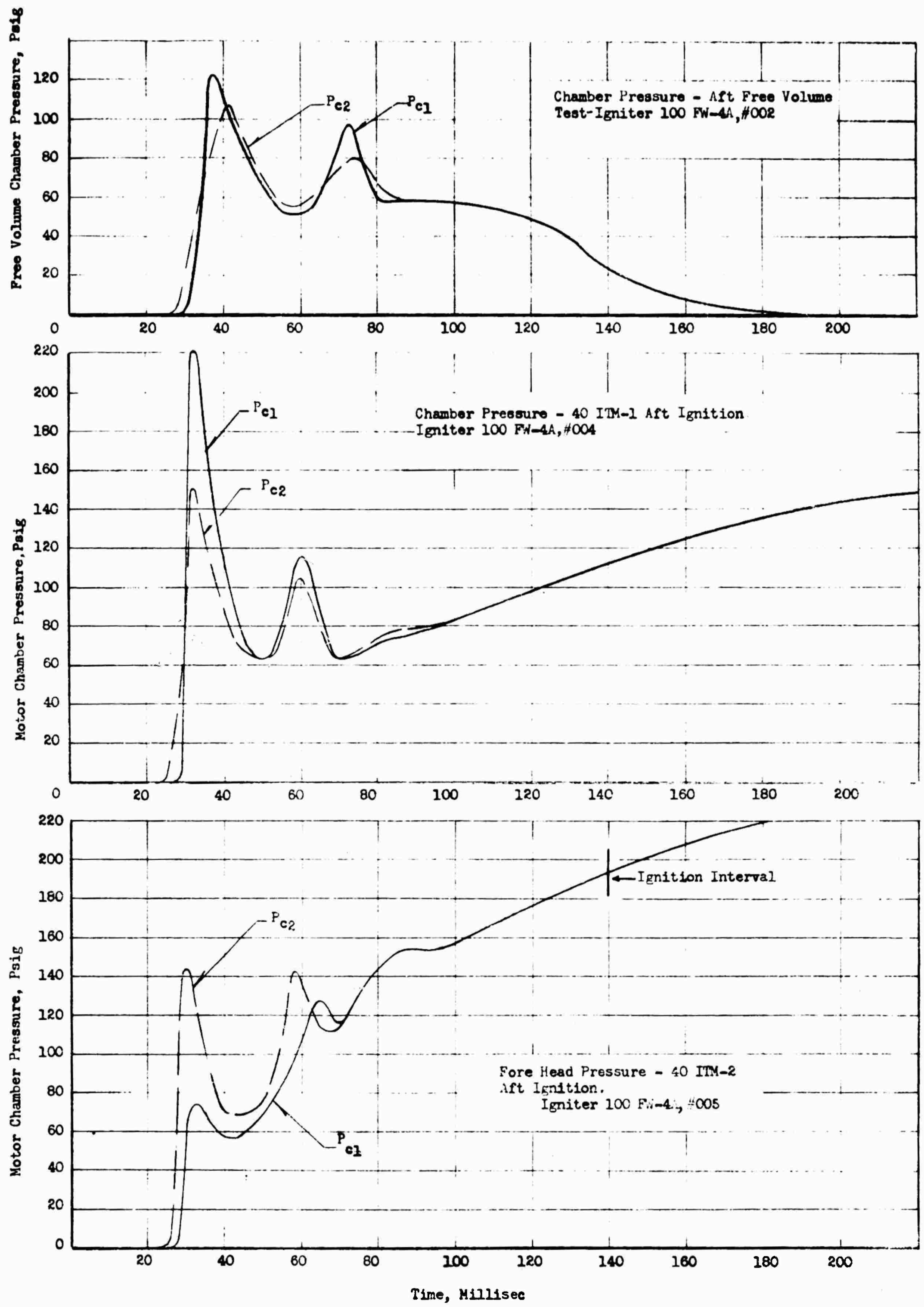
Igniter Gas Circulation, t=0.055 sec



Motor Ignition, t=0.070 sec

Motor 40 ITM-2 Ignition Sequence

Figure 27



P_{c1} - Forward Head Pressure

P_{c2} - Pressure 21-in. from Forward Head

Composite Pressure-vs-Time Curves for 40 ITM-1, 40 ITM-2 and Free-Volume Chamber

Figure 28

Postfiring View, Igniter and Holding Tube, Motor 40 ITM-2
(Photo 7-62S 18364)

Figure 29

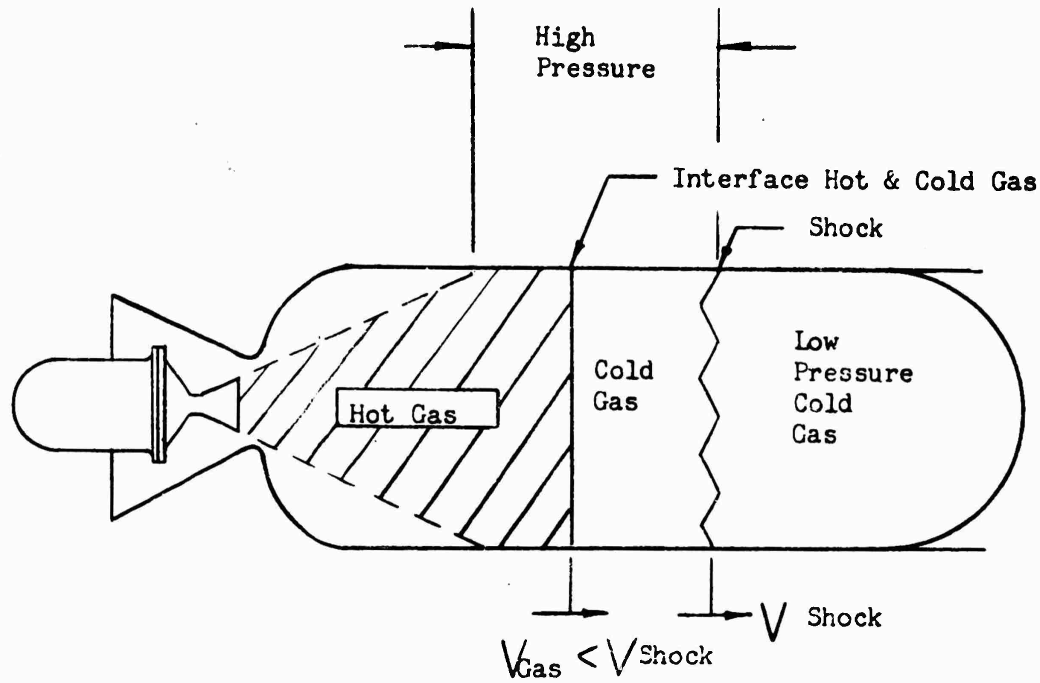
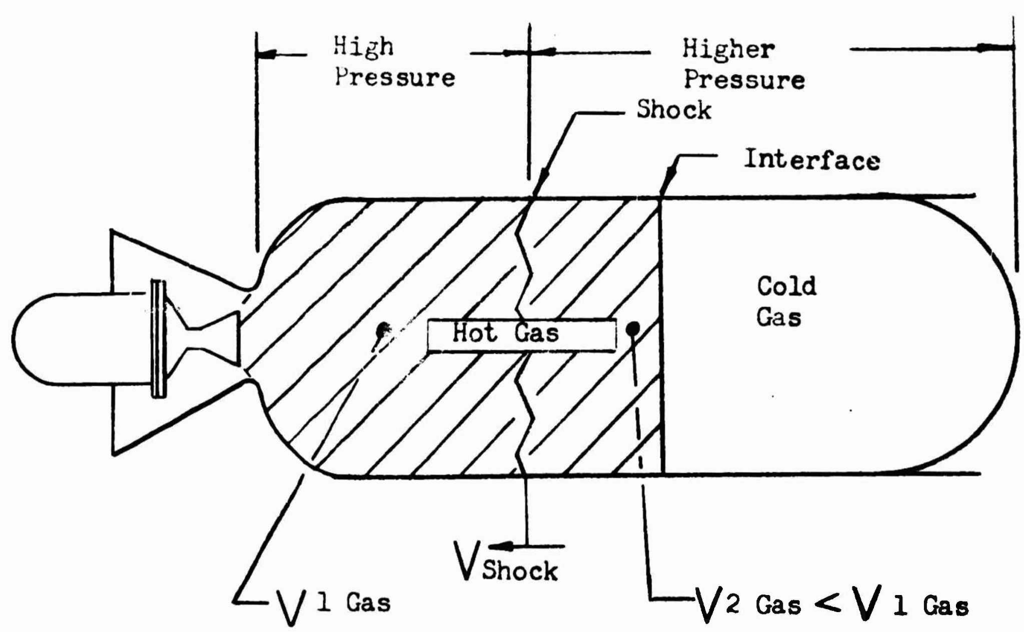
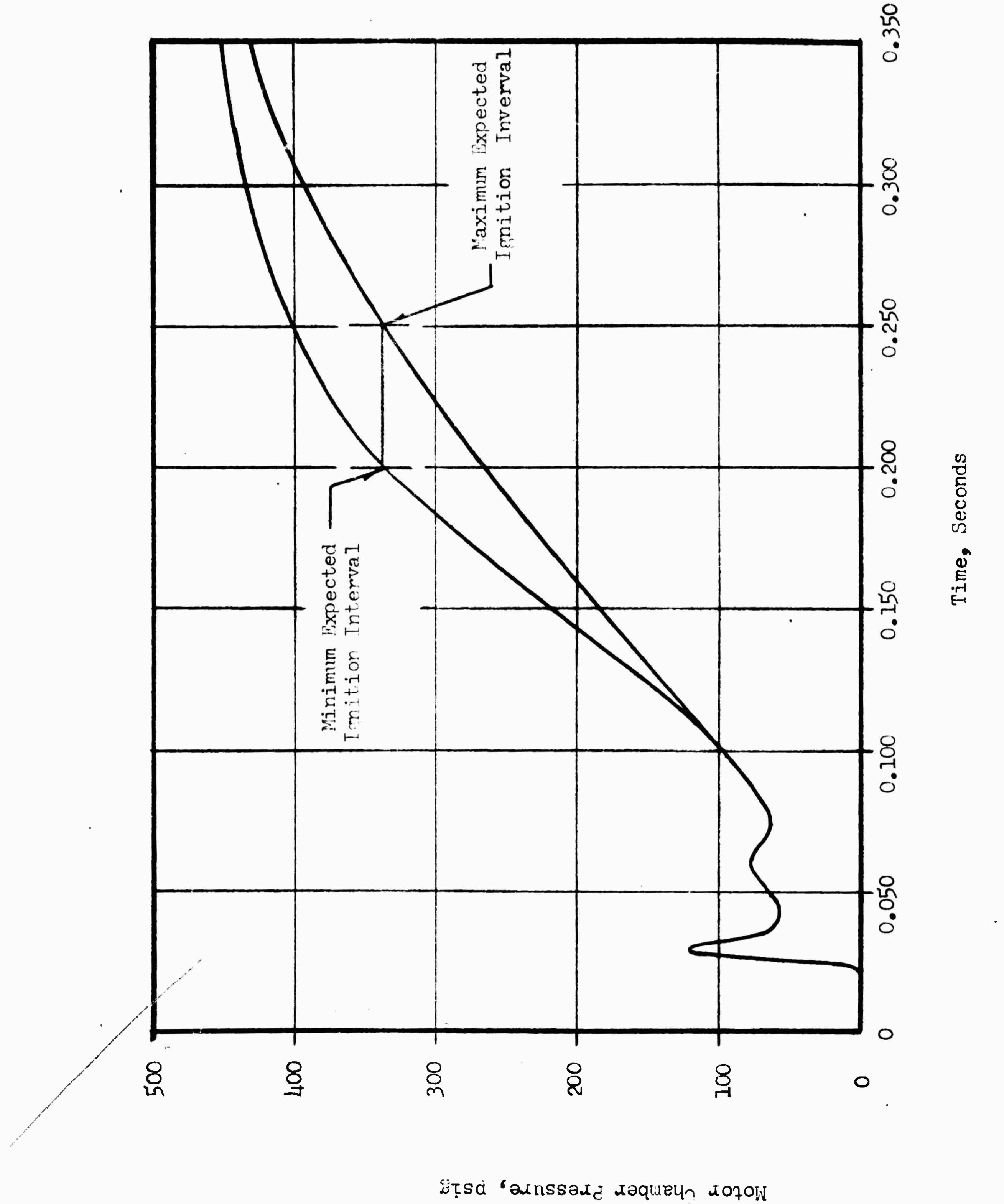


Figure 30B



Aft-End Ignition Gas Dynamic Model

Figure 30



Predicted Ignition Performance, Motor 100 FW-4

Figure 31

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Aerojet-General Corporation
Sacramento, California

FINAL REPORT, AFT-END IGNITION, LARGE SOLID-ROCKET PROGRAM (PHASE II)

September 1962 (Program 623A) (Report No. SSD-TDR-62-103) (AF 04(611)-8012)

This technical report furnishes information on the development program conducted to provide a reliable aft-end igniter for motor 100 FW-4 and to investigate the gas dynamics of aft-end ignition.

In addition to the primary goal of developing an aft-end igniter for 100 FW-4, other information obtained during the program included (1) gas flow conditions during aft-end ignition, (2) igniter gas penetration up the motor bore, (3) igniter charge-weight requirements for aft-ignition, and (4) effects of igniter duration and mass flow rate on aft-end ignition performance.

Alclojet igniter Models 51 and 52 were used in the test program and both were found to give satisfactory aft-end ignition. However, Model 52 was found to be more desirable because of a longer chamber pressurization.

UNCLASSIFIED

1. Igniters, Rocket (Alclojet Models 51 and 52)
2. Igniters - Development
3. Igniters - Material
4. Igniters - Performance
5. Igniters - Test Results
6. Gas Flow - Compressible Flow
7. Gas Flow - Subsonic Flow
8. Gas Flow - Supersonic Flow
9. Gas Flow - Transonic Flow
10. Gas Flow - Analysis Rocket Motors (40 ITM-2, -2)

Aerojet-General Corporation
Sacramento, California

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